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Mass loss of rotating stars at very low metallicity

Georges Meynet[*]
Astronomical Observatory of Geneva University
E-mail: `georges.meynet@obs.unige.ch`

André Maeder
Astronomical Observatory of Geneva University
E-mail: `Andre.Maeder@obs.unige.ch`

Raphael Hirschi
Dpt. of Physics and Astronomy, Basel University
E-mail: `Raphael.Hirschi@unibas.ch`

Sylvia Ekström
Astronomical Observatory of Geneva University
E-mail: `Sylvia.Ekstrom@obs.unige.ch`

Cristina Chiappini
Osservatorio Astronomico di Trieste and Astronomical Observatory of Geneva University
E-mail: `Christina.Chiappini@obs.unige.ch`

Some indirect observations, as the high fraction of Be stars[†]at low metallicity, or the necessity for massive stars to be important sources of primary nitrogen, seem to indicate that very metal poor stars were fast rotators. As a consequence of this fast rotation, these stars, contrarily to current wisdom, might lose large amounts of mass during their lifetime. In this paper, we review various mechanisms triggered by rotation which may induce strong mass loss at very low metallicity. The most efficient process comes from surface enrichments in CNO elements which then drive mass loss by stellar winds. Due to this process, a fast rotating 60 $M_\odot$ with metallicities in the range of $Z = 10^{-8}$ and 10^{-5}, can lose between 30 and 55% of its initial mass. This rotationally wind ejected material participates to the chemical evolution of the interstellar medium, enriching it exclusively in H- and He-burning products. In particular, metal poor fast rotating stars may play a key role for explaining the origin of the peculiar abundance pattern observed at the surface of the extremely metal-poor C-rich stars, for explaining the chemical inhomogeneities observed in globular clusters, and the presence of stars in ω Cen with a very high helium content .

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[*] Speaker.

[†] stars with rotational velocities near the critical limit.

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1. Radiation driven stellar winds from non-rotating metal poor stars

Current wisdom considers that very metal poor stars lose no or very small amounts of mass through radiatively driven stellar winds. This comes from the fact that when the metallicity is low, the number of absorbing lines is small and thus the coupling between the radiative forces and the matter is weak. Wind models imposes a scaling relation of the type

$$\dot{M}(Z) = \left(\frac{Z}{Z_\odot}\right)^\alpha \dot{M}(Z_\odot), \tag{1.1}$$

where $\dot{M}(Z)$ is the mass loss rate when the metallicitity is equal to Z and $\dot{M}(Z_\odot)$ is the mass loss rate for the solar metallicity, Z being the mass fraction of heavy elements. In the metallicity range from 1/30 to 3.0 times solar, the value of α is between 0.5 and 0.8 according to stellar wind models ([1]; [2]; [3]). Such a scaling law implies for instance that a non-rotating 60 $M_\odot$ with $Z = 0.02$ ends its stellar life with a final mass of 14.6 $M_\odot$, the same model with a metallicity of $Z = 0.00001$ ends its lifetime with a mass of 59.57 $M_\odot$ (cf. models of [4] and [34] with $\alpha = 0.5$).

Thus one can expect that the metal poor 60 $M_\odot$ star will give birth to a black hole. In that case, the whole stellar mass may disappear in the remnant preventing the star from enriching the interstellar medium in new synthesized elements. The metal rich model will probably leave a neutron star and contribute to the enrichment of the ISM through both the wind and supernova ejecta. Let us note that a star which loses a lot of material by stellar winds may differently enrich the interstellar medium in new elements, compared to a star which would have retained its mass all along until the supernova explosion. As [5] pointed out, when the stellar winds are strong, material partially processed by the nuclear reactions will be released, favoring some species (as helium and carbon which would be otherwise partially destroyed if remained locked into the star) and disfavoring other ones (as e.g. oxygen which would be produced by further transformation of the species which are wind-ejected).

Thus mass loss has very important consequences, but as said above, one expects no or very weak stellar winds at low metallicity from non-rotating stars. Now, one knows that stars are rotating and that rotation may change all the outputs of the stellar models, in particular the way they are losing mass. Indirect indications, as the presence of numerous Be stars (stars near the critical limit) in metal poor clusters ([32]), the necessity for massive stars to be efficient producers of primary nitrogen ([27]; [28]) point toward a higher proportion of fast rotators in metal poor regions. Thus it appears worthwhile to reconsider the question of the quantity of mass lost by fast rotating stars in metal poor region. This is the point we want to address in this paper.

2. General effects of rotation

Rotation induces many processes in stellar interior (see the review by [35]). In particular, it drives instabilities which transport angular momentum and chemical species. Assuming that the star rapidly settles into a state of shellular rotation (constant angular velocity at the surface of isobars), the transport equations due to meridional currents and shear instabilities can be consistently obtained ([6]). Since the work by J.-P. Zahn, various improvements have been brought to the formulas giving the velocity of the meridional currents ([7]), those of the various diffusive coefficients describing the effects of shear turbulence ([8]; [9]; [37]; [38]), as well as the effects of rotation on the mass loss ([10]; [11]; [12]).

Let us recall a few basic results obtained from rotating stellar models:

1) Angular momentum is mainly transported by the meridional currents. In the outer part of the radiative envelope these meridional currents transport angular momentum outwards. During the Main-Sequence phase, the core contracts and the envelope expands. The meridional currents imposes some coupling between the two, slowing down the core and accelerating the outer layers. In the outer layers, the velocity of these currents becomes smaller when the density gets higher, *i.e.*, for a given initial mass, when the metallicity is lower.

2) The chemical species are mainly transported by shear turbulence (at least in absence of a magnetic fields; when a magnetic fields is amplified by differential rotation as in the Tayler-Spruit dynamo mechanism [24], the main transport mechanism is meridional circulation [39]). During the Main-Sequence this process is responsible for the nitrogen enhancements observed at the surface of OB stars (see e.g. [42]). The shear turbulence is stronger when the gradients of the angular velocity are stronger. Due to point 1 above, the gradients of Ω are stronger in metal poor stars and thus the mixing of the chemical elements will be stronger in these stars. Some observations indicate that this might well be the case ([25]; [26]). Let us note also that the efficiency of the mixing will vary from one element to another. If an element is strongly and rapidly built up in the convective core, it will diffuse by rotational mixing more rapidly in the radiative envelope than an element with a smoother gradient between the convective core and the radiative envelope. This explains why the stellar surface will be more rapidly enriched in nitrogen than in helium.

In addition to these internal transport processes, rotation also modifies the physical properties of the stellar surface. Indeed the shape of the star is deformed by rotation (a fact which is now put in evidence observationally thanks to the interferometry, see [13]). Rotation implies a non-uniform brightness (also now observed, see [14]). The polar regions are brighter that the equatorial ones. This is a consequence of the hydrostatic and radiative equilibrium (von Zeipel theorem [15]). In addition, as a result of the internal transport processes, the surface velocity and the surface chemical composition are modified.

The various processes described above are worthwhile to keep in mind since they all play some role in promoting mass loss in metal poor stars. We can classify the effects of rotation on mass loss in three categories.

1. The structural effects of rotation.
2. The changes brought by rotation on the radiation driven stellar winds.
3. The mechanical wind induced by rotation at break-up.

Let us now consider in turn these various processes.

3. Structural effects of rotation on mass loss

Rotation, by changing the chemical structure of the star, modifies its evolution. For instance, moderate rotation at metallicities of the Small Magellanic Cloud (SMC) favors redward evolution

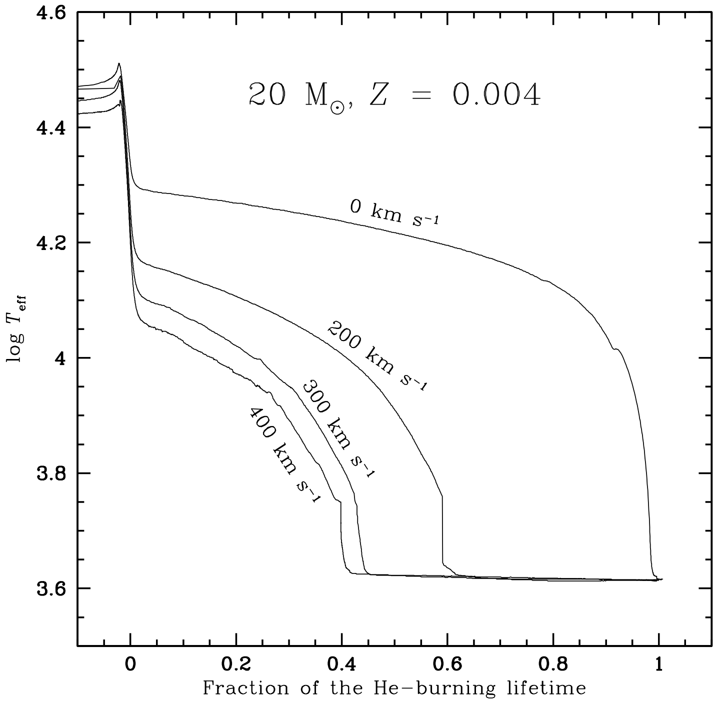

Figure 1: Evolution of the $T_{\rm eff}$ as a function of the fraction of the lifetime spent in the He–burning phase for 20 $M_\odot$ stars with different initial velocities.

in the Hertzsprung-Russel diagram. This behavior is illustrated in Fig. 1 and can account for the high number of red supergiants observed in the SMC ([16]), an observational fact which is not at all reproduced by non-rotating stellar models.

Now it is well known that the mass loss rates are greater when the star evolves into the red part of the HR diagram, thus in this case, rotation modifies the mass loss indirectly, by changing the evolutionary tracks. The $\upsilon_{\rm ini} = 0$, 200, 300 and 400 km s^{-1} models lose respectively 0.14, 1.40, 1.71 and 1.93 $M_\odot$ during the core He-burning phase (see Table 1 in [16]). The enhancement of the mass lost reflects the longer lifetimes of the red supergiant phase when velocity increases. Note that these number were obtained assuming that the same scaling law between mass loss and metallicity applies during the red supergiant phase. If, during this phase, mass loss comes from continuum-opacity driven wind then the mass-loss rate will not depend on metallicity (see the review by [45]). In that case, the redward evolution favored by rotation would have a greater impact on mass loss than that shown by the computations shown above.

Of course, such a trend cannot continue forever. For instance, at very high rotation, the star will have a homogeneous evolution and will never become a red supergiant ([40]). In this case, the mass loss will be reduced, although this effect will be somewhat compensated by two other processes: first by the fact that the Main-Sequence lifetime will last longer and, second, by the fact that the star will enter the Wolf-Rayet phase (a phase with high mass loss rates) at an earlier stage of its evolution.

4. Radiation driven stellar winds with rotation

The effects of rotation on the radiation driven stellar winds result from the changes brought by rotation to the stellar surface. They induce changes of the morphologies of the stellar winds and increase their intensities.

4.1 Stellar wind anisotropies

Naively we would first guess that a rotating star would lose mass preferentially from the equator, where the effective gravity (gravity decreased by the effect of the centrifugal force) is lower. This is probably true when the star reaches the critical limit (i.e. when the equatorial surface velocity is such that the centrifugal acceleration exactly compensates the gravity), but this is not correct when the star is not at the critical limit. Indeed as recalled above, a rotating star has a non uniform surface brightness, and the polar regions are those which have the most powerful radiative flux. Thus one expects that the star will lose mass preferentially along the rotational axis. This is correct for hot stars, for which the dominant source of opacity is electron scattering. In that case the opacity only depends on the mass fraction of hydrogen and does not depends on other physical quantities such as temperature. Thus rotation induces anisotropies of the winds ([17];[18]). This is illustrated in Fig. 2. Wind anisotropies have consequences for the angular momentum that a star retains in its interior. Indeed, when mass is lost preferentially along the polar axis, little angular momentum is lost. This process allows loss of mass without too much loss of angular momentum a process which might be important in the context of the evolutionary scenarios leading to Gamma Ray Bursts. Indeed in the framework of the collapsar scenario ([41]), one has to accommodate two contradictory requirements: on one side, the progenitor needs to lose mass in order to have its H and He-rich envelope removed at the time of its explosion, and on the other hand it must have retained sufficient angular momentum in its central region to give birth to a fast rotating black-hole.

4.2 Intensities of the stellar winds

The quantity of mass lost through radiatively driven stellar winds is enhanced by rotation. This enhancement can occur through two channels: by reducing the effective gravity at the surface of the star, by increasing the opacity of the outer layers through surface metallicity enhancements due to rotational mixing.

- *reduction of the effective gravity:* The ratio of the mass loss rate of a star with a surface angular velocity Ω to that of a non-rotating star, of the same initial mass, metallicity and lying at the same position in the HR diagram is given by ([12])

  $$\frac{\dot{M}(\Omega)}{\dot{M}(0)} \simeq \frac{(1-\Gamma)^{\frac{1}{\alpha}-1}}{\left[1-\frac{4}{9}(\frac{v}{v_{\mathrm{crit},1}})^2-\Gamma\right]^{\frac{1}{\alpha}-1}}\ , \tag{4.1}$$

  where Γ is the electron scattering opacity for a non–rotating star with the same mass and luminosity, α is a force multiplier ([19]). The enhancement factor remains modest for stars with luminosity sufficiently far away from the Eddington limit ([12]). Typically, $\frac{\dot{M}(\Omega)}{\dot{M}(0)} \simeq 1.5$ for main-sequence B–stars. In that case, when the surface velocity approaches the critical

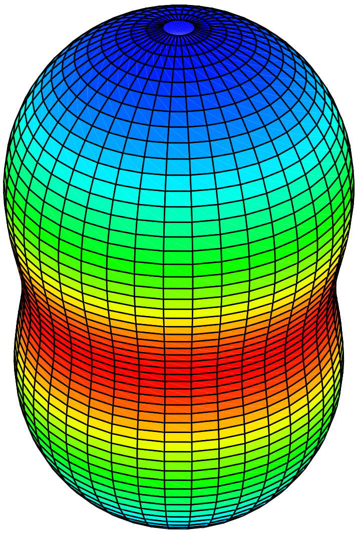

Figure 2: Iso-mass loss distribution for a 120 $M_\odot$ star with Log $L/L_\odot$=6.0 and $T_{\rm eff}$ = 30000 K rotating at a fraction 0.8 of critical velocity.

limit, the effective gravity decreases and the radiative flux also decreases. Thus the matter becomes less bound when, at the same time, the radiative forces become also weaker. When the stellar luminosity approaches the Eddington limit, the mass loss increases can be much greater, reaching orders of magnitude. This comes from the fact that rotation lowers the maximum luminosity or the Eddington luminosity of a star. Thus it may happen that for a velocity still far from the classical critical limit, the rotationally decreased maximum luminosity becomes equal to the actual luminosity of the star. In that case, strong mass loss ensues and the star is said to have reached the $\Omega\Gamma$ limit ([12]).

- *Effects due to rotational mixing:* During the core helium burning phase, at low metallicity, the surface may be strongly enriched in both H-burning and He-burning products, *i.e.* mainly in nitrogen, carbon and oxygen. Nitrogen is produced by transformation of the carbon and oxygen produced in the He-burning core and which have diffused by rotational mixing in the H-burning shell ([34]). Part of the carbon and oxygen produced in the He-core also diffuses up to the surface. Thus at the surface, one obtains very high value of the CNO elements. For instance a 60 $M_\odot$ with Z=10^{-8} and $\upsilon_{\rm ini} = 800$ km s^{-1} has, at the end of its evolution, a CNO content at the surface equivalent to 1 million times its initial metallicity! In the present models, we have applied the usual scaling laws linking the surface metallicity to the mass loss rates (see Eq. 1). In that case, one obtains that the star loses due to this process more

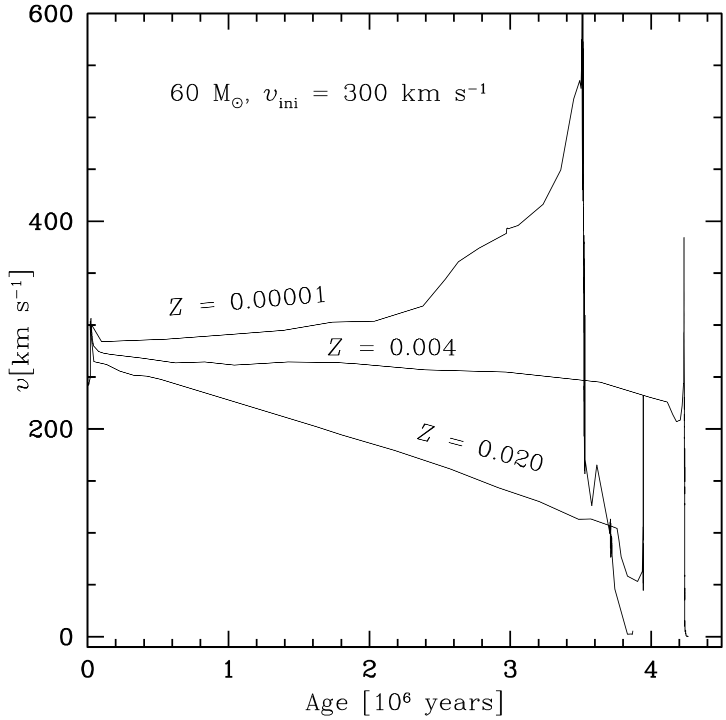

Figure 3: Evolution of the surface velocities for a 60 $M_\odot$ star with 3 different initial metallicities.

than half of its initial mass (see Table 1).

5. Mechanical winds induced by rotation

As recalled above, during the Main-Sequence phase the core contracts and the envelope expands. In case of local conservation of the angular momentum, the core would thus spin faster and faster while the envelope would slow down. In that case, it can be easily shown that the surface velocity would evolve away from the critical velocity (see e.g. [22]). In models with shellular rotation however an important coupling between the core and the envelope is established through the action of the meridional currents. As a net result, angular momentum is brought from the inner regions to the outer ones. Thus, would the star lose no mass by radiation driven stellar winds (as is the case at low Z), one expects that the surface velocity would increase with time and would approach the critical limit (see Fig. 3). In contrast, when radiation driven stellar winds are important, the timescale for removing mass and angular momentum at the surface is shorter than the timescale for accelerating the outer layers by the above process and the surface velocity decreases as a function of time. It evolves away from the critical limit. Thus, an interesting situation occurs: when the star loses little mass by radiation driven stellar winds, it has more chance to lose mass by a mechanical wind. On the other hand, when the star loses mass at a high rate by radiation driven mass loss then it has no chance to reach the critical limit and thus to undergo a mechanical wind. We discuss further below the possible importance of this mechanical wind.

6. Discussion

At this point it is interesting to discuss three aspects of the various effects described above. First what are the main uncertainties affecting them? Second, what are their relative importance? And finally what are their consequences for the interstellar medium enrichment?

6.1 Uncertainties

In addition to the usual uncertainties affecting the radiation driven mass loss rates, the above processes poses three additional problems:

1. *What does happen when the CNO content of the surface increases by six orders of magnitude as was obtained in the 60 $M_\odot$ model described above?* Can we apply the usual scaling law between Z and the mass losses? This is what we have done in our models (using $\alpha = 0.5$), but of course this should be studied in more details by stellar winds models. For instance, for WR stars, [46] have shown that at $Z = Z_\odot/30$, 60% of the driving is due to CNO elements and only 10% to Fe. Here the high CNO surface enhancements result from rotational mixing which enrich the radiative outer region of the star in these elements, but also from the fact that the star evolves to the red part of the HR diagram, making an outer convective zone to appear. This convective zone plays an essential role in dredging up the CNO elements at the surface. Thus what is needed here is the effects on the stellar winds of CNO enhancements in a somewhat red part of the HR diagram (typical effective temperatures of the order of Log $T_{\rm eff} \sim 3.8$).

2. *Do stars can reach the critical limit?* For instance, [21] obtain that during pre-main sequence evolution of rapidly rotating massive stars, “equatorial mass loss” or “rotational mass ejection” never occur (see also [20]). In these models the condition of zero effective gravity is never reached. However, these authors studied pre-main sequence evolution and made different hypotheses on the transport mechanisms than in the present work. Since they were interested in the radiative contraction phase, they correctly supposed that “the various instabilities and currents which transport angular momentum have characteristic times much longer than the radiative-contraction time”. This is no longer the case for the Main-Sequence phase. In our models, we consistently accounted for the transport of the angular momentum by the meridional currents and the shear instabilities. A detailed account of the transport mechanisms shows that they are never able to prevent the star from reaching the critical velocity. Another difference between the approach in the work of [21] and ours is that [21] consider another distribution of the angular velocity than in our models. They supposed constant Ω on cylindrical surface, while here we adopted, as imposed by the theory of [6], a “shellular rotation law”. They resolved the Poisson equation for the gravitational potential, while here we adopted the Roche model. Let us note that the Roche approximation appears justified in the present case, since only the outer layers, containing little mass, are approaching the critical limit. The majority of the stellar mass has a rotation rate much below the critical limit and is thus not strongly deformed by rotation. Thus these differences probably explain why in our models we reach situations where the effective gravity becomes zero.

3. *What does happen when the surface velocity reaches the critical limit?* Let us first note that when the surface reaches the critical velocity, the energy which is still needed to make equatorial matter to escape from the potential well of the star is still important. This is because the gravity of the system continues of course to be effective all along the path from the surface to the infinity and needs to be overcome. If one estimates the escape velocity from the usual equation energy for a piece of material of mass m at the equator of a body of mass M, radius R and rotating at the critical velocity,

$$\frac{1}{2}m\upsilon^2_{\rm crit}+\frac{1}{2}m\upsilon^2_{\rm esc}-\frac{GMm}{R}=0, \tag{6.1}$$

one obtains, using $\upsilon^2_{\rm crit}=GM/R$ that the escape velocity is simply reduced by a factor $1/\sqrt{2}=0.71$ with respect to the escape velocity from a non-rotating body [1]. Thus the reduction is rather limited and one can wonder if matter will be really lost. A way to overcome this difficulty is to consider the fact that, at the critical limit, the matter will be launched into a keplerian orbit around the star. Thus, probably, when the star reaches the critical limit an equatorial disk is formed like for instance around Be stars. Here we suppose that this disk will eventually dissipate by radiative effects and thus that the material will be lost by the star.

Practically, in the present models, we remove the supercritical layers. This removal of material allows the outer layers to become again subcritical at least until secular evolution will bring again the surface near the critical limit (see [23] for more details in this process). Secular evolution during the Main-Sequence phase triggers two counteracting effects: on one side, the stellar surface expands. Local conservation of the angular momentum makes the surface to slow down and the surface velocity to evolve away from the critical limit. On the other hand, meridional circulation continuously brings angular momentum to the surface and accelerates the outer layers. This last effect in general overcomes the first one and the star rapidly reach again the critical limit. How much mass is lost by this process? As seen above, the two above processes will maintain the star near the critical limit for most of the time. In the models, we adopt the mass loss rate required to maintain the star at about 95-98% of the critical limit. Such a mass loss rate is imposed as long as the secular evolution brings back the star near the critical limit. In general, during the Main-Sequence phase, once the critical limit is reached, the star remains near this limit for the rest of the Main-Sequence phase. At the end of the Main-Sequence phase, evolution speeds up and the local conservation of the angular momentum overcomes the effects due to meridional currents, the star evolves away from the critical limit and the imposed "critical" mass loss is turned off.

6.2 Importance of the various effects on mass loss induced by rotation

The processes which are the most important for metal poor stars are the reaching of the critical limit (both the classical limit and the $\Omega\Gamma$-limit) and the increase of the surface metallicity by the concomitant effect of rotational diffusion and dredging-up by an outer convective zone.

In order to quantify the importance of the various effects discussed above, we compare in Table 1 four 60 $M_\odot$ with an initial velocity of 800 km s^{-1} at four different metallicities, $Z=0$

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[1] We suppose here that the vector $\upsilon_{\rm esc}$ is normal to the direction of the vector $\upsilon_{\rm crit}$.

Z	$\Omega/\Omega_{\rm crit}$	Δ M$_{\rm MS}$	Δ M$_{\rm PMS}$
0	0	0	0.0013 (0)
0	0.71	2.42	0.27 (0)
10^{-8}	0	0.18	0.09 (0)
10^{-8}	0.77	2.38	33.80 (0.85)
10^{-5}	0	0.21	0.22 (0)
10^{-5}	0.90	6.15	16.94 (0)
0.0005	0	0.78	13.29 (0)
0.0005	0.94	20.96	21.79 (17.15)

Table 1: Mass lost in solar masses by 60 M$_\odot$ non-rotating and rotating models at different metallicities during the MS and the post MS phases. The number in parenthesis in the last column indicates the mass lost during the WR phase. See text for the references of the stellar models.

([33]), 10^{-8}, 10^{-5} ([23]) and 10^{-3} (Decressin et al., submitted) and we give the mass lost during the MS and the post MS (PMS) phases. The mass lost by non-rotating models is also given.

From Table 1, we first note that a given value of the initial velocity (here 800 km s^{-1}) corresponds to lower value of $\Omega/\Omega_{\rm crit}$ at lower metallicity. This is a consequence of the fact that stars are more compact at low Z. Would we have kept $\Omega/\Omega_{\rm crit}$ constant one would have higher values of $\upsilon_{\rm ini}$ at low Z.

During the MS phase, we see that the non-rotating models lose nearly no mass. The rotating models, on the other hands, lose some mass when reaching the critical limit. For the Pop III star the critical limit is reached when the mass fraction of hydrogen at the center, X_c, is 0.35. For the models at Z= 10^{-8}, 10^{-5} and 0.0005, the critical limit is reached respectively when X_c is equal to 0.40, 0.56 and 0.65. Thus at higher metallicity, the critical limit is reached earlier. This behavior comes from two facts: first keeping $\upsilon_{\rm ini}$ constant implies higher $\Omega/\Omega_{\rm crit}$ at higher Z, then, meridional currents, which accelerate the outer layers are more rapid at higher metallicities.

The mass lost after the Main-Sequence phase remains very modest for non-rotating stars, except for the model at $Z = 0.0005$. For the rotating models, except in the case of the Pop III models, all models lose great amounts of material. In the case of the models with $Z = 10^{-8}$ and 10^{-5}, the main effect responsible for the huge mass loss is the surface enrichments in CNO elements. In the case of the $Z = 0.0005$, no such effect is observed, however the star, as a result of the high mass loss during the MS phase and also due to rotational mixing, has a long WR phase, during which most of the mass is lost. The Pop III model on the other hand loses little amount of mass during the post-MS phase. This comes from the fact that the star evolves only at the very end of its evolution in the red part of the HR diagram, preventing thus an efficient dredging up of the CNO elements at the surface. Thus the surface enhancements remain modest and occur during a too short phase for having an important impact on mass loss. On the other hand, it would be interesting to compute models with higher initial values of $\Omega/\Omega_{\rm crit}$.

As a general conclusion, we see that the quantity of mass lost very much depends on rotation in metal poor regions. Moreover, the lost material is enriched in new synthesized elements like helium, carbon, nitrogen and oxygen and thus will participate to the chemical evolution of the interstellar medium. Short comments on this point are made in the paragraph below.

6.3 Interesting consequences

The effects of rotation in metal poor stellar models have an impact on the stellar populations and the nucleosynthesis. Some of these effects are mainly due to the more efficient mixing obtained in metal poor stars and do not much depend on the mass loss induced by rotation, others are consequences of both effects.

Among the effects mainly due to enhanced rotational mixing, let us mention the fact that fast rotating massive stars might be very efficient sources of primary nitrogen in metal poor regions ([27]; [28] and see the contribution by Chiappini et al. in this volume) and lead to different trends for C/O and N/O at very low metallicity. Other isotopes such as ^{13}C, ^{18}O could also be produced abundantly in such models.

Interesting consequences resulting from both enhanced rotational mixing and mass loss are:

- the possibility to explain the origin of the peculiar abundance pattern exhibited by the extremely metal poor C-rich stars. These stars could be formed from wind material of rotating massive stars or from material ejected, either in a mass transfer episode or by winds, from a rotating E-AGB star ([23], Hirschi, submitted).

- to provide an explanation for the origin of the helium-rich stars in ω Cen. The presence of a blue ZAMS sequence in this cluster (in addition to a red sequence which is about a factor two less rich in iron) is interpreted as the existence in this cluster of very helium rich stars. Typically stars on the blue sequence would have, according to stellar models, a mass fraction of helium of 0.40, while stars on the red sequence would only have an helium mass fraction of 0.25 ([29]). We have proposed that the helium-rich stars could be formed from wind material of fast rotating massive stars ([30]). This material would indeed have the appropriate chemical composition for accounting for the abundance patterns observed in the blue sequence.

- Interestingly, fast rotating massive stars, losing mass at the critical limit, could also contribute in providing material for forming second generation stars in globular clusters. Such stars would present peculiar surface abundances, relics of their nuclear-processing in the fast rotating massive stars (see [47], and also the contributions by Charbonnel and Prantzos in the present volume).

7. Conclusions

It is now a well known fact that rotation is a key feature of the evolution of stars. For metallicities between those of the Small Magellanic Cloud and of the solar neighborhood, rotating models better reproduce the observed characteristics of stars than non-rotating models (see e.g. the discussion in [23]). From this argument alone, one would expect that they would do the same in metal poor regions. Of course at very low metallicity, direct comparisons between massive star models and observed stars are no longer possible. Thus it is particularly important in this case to first check the models in metallicity range where such comparisons are possible. When the same physical processes as those necessary to obtain good fits at high metallicity are accounted for in metal poor stars, one notes that stars are on one hand strongly mixed and on the other hand may lose large amounts of material. These features might be very helpful for explaining numerous puzzling observational facts concerning metal poor stars as seen above. Moreover, such models stimulate new questions which can be the subjects of future works:

- One can wonder what would be the contribution of very fast rotating Pop III massive stars to the ionizing flux. These stars would follow an homogeneous evolution, evolve in the blue side of the HR diagram, would have their lifetimes increased and would become WR stars. For all these reasons, they would likely be important sources of ionizing photons.

- What would be the ultimate fate of such fast rotating Pop III stars? Would they give birth to collapsars as proposed by [43] and [44]?

- If pair instability supernovae have left no nucleosynthetic sign of their existence in observed metal poor star, is this because no sufficiently high massive stars have ever formed? Or, if formed, might these stars have skipped the Pair Instability regime due to strong mass loss triggered by fast rotation?

- Does the dynamo mechanism of Tayler-Spruit work in Pop III stars? This mechanism needs a small pristine magnetic field which will be amplified at the expense of the differential rotational energy. But does this pristine magnetic field exist in this case? In case the mechanism is working, how its effects vary as a function of the metallicity?

- Could the first generations of massive stars be important producers of helium as was suspected long time ago by [36]?

- What was the distribution of the rotational velocities at different metallicities? Is this distribution the same in the field and in dense clusters (like globular clusters)? As recalled above, some indirect observations indicate that the distribution might be biased toward fast rotators at low metallicity. Are there any other indirect hints supporting this view? What would be the physical mechanism responsible for such a trend? (Shorter disk locking episode in metal poor regions?).

The list above is not exhaustive. It simply reflects the richness of the subject which will certainly become a very fruitful area of research in the coming years.

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