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MASSIVE STAR EVOLUTION WITH MASS LOSS AND ROTATION

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RESUMEN

La rotación estelar influye los caminos evolutivos, los tiempos de vida, las determinaciones de masa, la composición química de las estrellas masivas, así como la formación de supergigantes rojas y estrellas WR. Las tasas de pérdida de masa anisotrópica de estrellas masivas en rotación es una característica esencial para analizar nebulosas LBV. También conduce a estrellas WO con He escaso o nulo, manteniendo al mismo tiempo una rotación lo suficientemente alta como para producir un precursor de GRB.

ABSTRACT

Stellar rotation influences the tracks, the lifetimes, the mass determinations, the chemical composition of massive stars, as well as the formation of red supergiants and WR stars. The anisotropic mass loss rates of massive rotating stars is an essential feature for accounting LBV nebulae. It also leads to WO stars with little or no He left, keeping at the same time a high enough rotation to produce a possible GRB precursor.

Key Words: stars: evolution — stars: mass loss — stars: rotation — stars: Wolf-Rayet

1. A GREAT ASTRONOMER

We all shall keep the memory of Virpi with her deep sense of observational astrophysics, perspicacity, high scientific productivity and kindness, all qualities which have enlightened her 40 years of a remarkable scientific activities. We are grateful to Virpi for what she has brought to us and to the field of massive stars.

It is appropriate here to collect a few marking points which influence the fundamental parameters and circumstellar interactions of massive stars.

2. ROTATION AND CIRCUMSTELLAR EFFECTS

Axial rotation has a deep influence on all stellar properties. One can distinguish 4 kinds of effects of rotation:

- The structural effects due to centrifugal force.
- The rotational mixing of chemical elements.
- The anisotropic stellar winds and the enhancements of the mass loss rates.
- The magnetic fields created by dynamos in rotating stars.

These various effects were studied in a series of papers (e.g Meynet & Maeder 2005; Maeder & Meynet 2005). The first effect has little consequence in the deep interior, however it modifies the stellar shape and determines the third effect. Potentially for a high enough rotation, all model outputs are deeply modified by rotation. We recall that rotation velocities are in general largely underestimated (Collins 2004), because the models used for estimating the $v \sin i$ assume a uniform brightness on the stellar surface. In reality, due to the von Zeipel theorem, which says that the flux is proportional to the effective gravity, the equatorial brightness is much lower than the polar one, this means that the contribution of the fast moving equatorial band to the line profiles is underweighted. If this effect is not accounted for, as is usual, the velocities above about 200 km s^{-1} are largely underestimated.

Due to the von Zeipel theorem, there is a much larger flux and a higher $T_{\rm eff}$ at the pole than at the equator. This latitudinal dependence of $T_{\rm eff}$ leads, when accounted for in the theory of radiative winds (Maeder & Meynet 2000), to asymmetric mass loss and to enhanced average mass loss rates. For a star hot enough to have electron scattering opacity from pole to equator, the iso-mass loss curve has a peanut-like shape (Figure 1), due to the fact that the pole is hotter ("$g_{\rm eff}$-effect"). For a rotating star with a lower $T_{\rm eff}$, a bistability limit, i.e., a steep increase of the opacity (Lamers 1995) may occur somewhere between the pole and equator. This "opacity–effect" produces an equatorial enhancement of the mass loss. In Figure 2, we show the model of a short shell ejection with mass loss corresponding to the peanut-shape, which compares well with the image of AG Carinae (Nota 1997).

The anisotropies of mass loss influence the loss of angular momentum. Polar mass loss removes mass,

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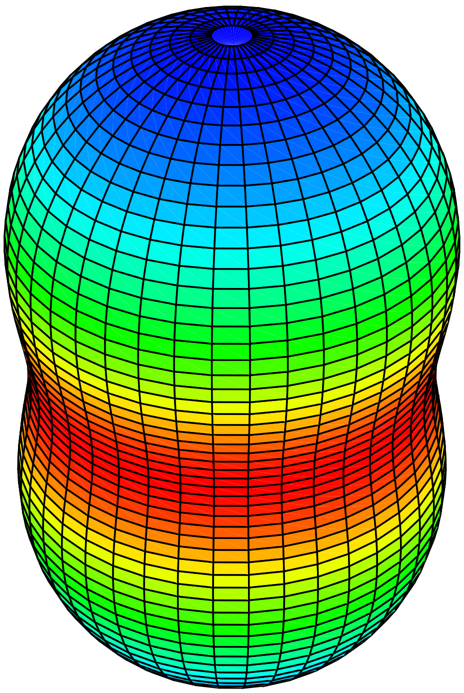

Fig. 1. Iso-mass loss distribution for a 120 $M_\odot$ star with $\log L/L_\odot = 6.0$ and $T_{\rm eff} = 30000$ K rotating at a fraction 0.80 of break-up velocity.

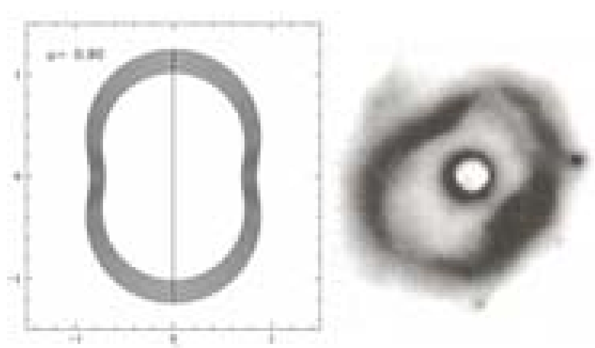

Fig. 2. Left: simulation of a short shell ejection by a massive star with anisotropic mass loss. Right: the nebulae around AG Carinae (Nota 1997).

but relatively little angular momentum. This has a great incidence on the evolution of the most massive stars with high rotation. The mass loss rate $\dot{M}(\Omega)$ of a rotating star compared to that $\dot{M}(0)$ of a non–rotating star at the same location in the HR diagram is given by (Maeder & Meynet 2000),

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

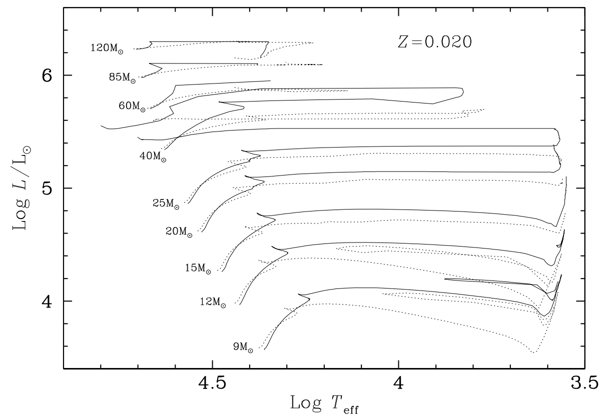

Fig. 3. HR diagram of massive stars with metallicity Z=0.02. The heavy lines represent the models with a rotation close to the observed average, the thin lines are for models without rotation.

where Γ is the Eddington factor, α the force multiplier (Lamers 1995) and $v_{\rm crit}$ the critical velocity. For a 10 $M_\odot$ star on the MS, $\dot{M}(\Omega)/\dot{M}(0)$ may reach 1.5. For the most luminous stars which have a value Γ close to 1.0, this may be orders of magnitude. This occurs when the star approaches the $\Omega\Gamma$-Limit, i.e. the critical limit determined by both rotation and radiation. Even for a rather low rotation velocity of, say, 50 km s^{-1}, a star with a high Γ will reach critical velocity during its MS evolution. This happens because the critical velocity decreases during MS evolution.

The change of gravity and $T_{\rm eff}$ at the $\Omega\Gamma$–Limit favors the apparition of convection in the equatorial regions. This applies, both when radiation dominates and when the break–up is produced by rotation only (Ω–Limit). This has many important consequences: first it gives the star a 2–D structure, second it may introduce deviations from the von Zeipel theorem and third it may give an additional kick to radiative winds for ejecting matter. These effects and their consequences are now being investigated.

3. HR DIAGRAM AND LIFETIMES

Figure 3 shows the HR diagram of models with and without rotation. With rotation the MS phase is more extended, due to internal mixing which extends convective cores. As a consequence, the MS lifetimes are also longer. Isochrones were calculated from models with an average rotation during the MS phase of 140 km s^{-1} (Meynet & Maeder 2000), which show that if we assign cluster ages from these isochrones, we obtain ages typically 25% larger than from the standard models without rotation. For av-

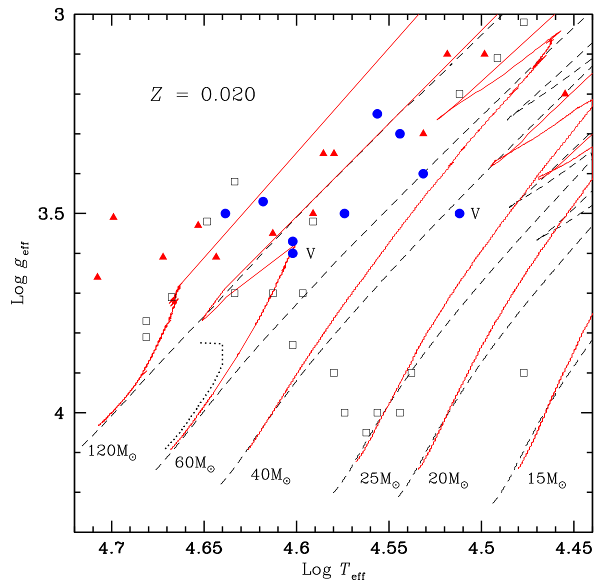

Fig. 4. Evolutionary tracks in the $\log g_{\rm eff}$ vs. $\log T_{\rm eff}$ plane where $g_{\rm eff}$ is the effective surface gravity. The dashed and continuous lines are for the non–rotating and rotating (with an initial velocity $v_{\rm ini}$ = 300 km s^{-1}) models respectively. The dotted track corresponds to a faster rotating 60 $M_\odot$. The observations by Herrero et al. (2000) are indicated.

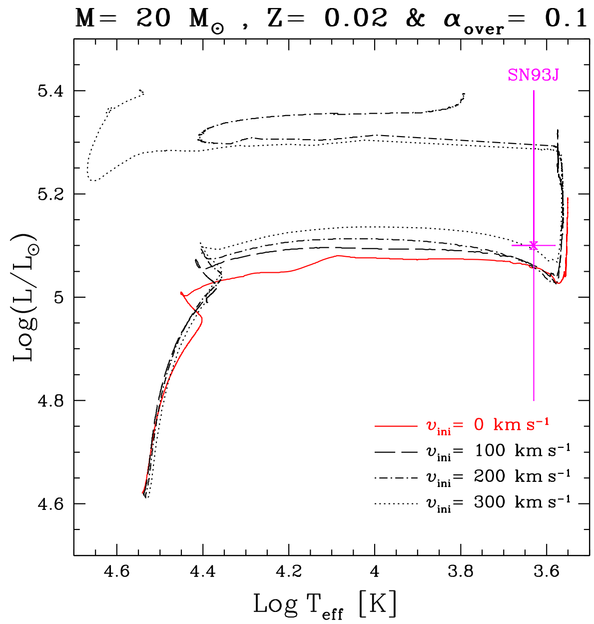

Fig. 5. Details of the evolutionary tracks in in the blue and red supergiant phases for 20 $M_\odot$ stars of different initial rotation velocities, from Hirschi et al. (2004).

erage velocities of about 220 km/s, the difference in the age estimates would be larger.

Figure 4 shows the tracks in the $\log g_{\rm eff}$ vs. $\log T_{\rm eff}$ plot. If we assign a mass from $\log g$ and $\log T_{\rm eff}$ to a rotating star on the basis of a track without rotation, we obtain a mass which may be up to a factor of 2 too large. Tracks with the appropriate rotation have to be used to estimate stellar masses. The non–respect of this prescription is likely the main explanation of the so–called problem of the mass discrepancy.

Figure 5 shows that rotation first favors the evolution of massive stars towards the red supergiant phase. The effects also depend on the mass and they are illustrated here for a 20 $M_\odot$ star. For low rotation, the star spends most of the He–burning phase in the blue and just reaches the red supergiant phase at the end of this phase. A moderate rotation leads the star to rapidly move to the red and to spend more time in the red supergiant phase (Maeder & Meynet 2001). If the initial rotation is very high, the mass loss enhancement peels off the star enough to make it to move back to the blue as a supergiant with little envelope left (likely producing a SNII without a plateau in its light curve) or a WR star. These are very positive effects, particularly at low metallicity as in the SMC where there are lots of red supergiants, while it is well known that current models without rotation do not predict enough red supergiants. The inclusion of rotation has been able to solve this problem, which was quite embarrassing.

The comparison of the observed and predicted helium abundances and of N/C or N/H ratios in Main–Sequence OB stars and in supergiants is a key test about internal mixing. Enrichments in N/C up to a factor of 10 are observed (Crowther et al. 2006) for galactic B–supergiants in agreement with model predictions (Meynet & Maeder 2000). It is interesting to note that at lower Z, as in the SMC, these enrichments are much larger reaching a factor of 30 (Heap & Lanz 2004). This is quite in agreement with model predictions. The lower Z stars have much steeper internal gradients of angular velocity (for several reasons, one of them being the smaller radii), which drive a stronger internal mixing, as is observed.

4. PROPERTIES OF WOLF–RAYET STARS

Mass loss is essential in the formation of WR stars. However, the account for clumping has reduced the mass loss rates in OB stars as well as in WR stars (Vink et al. 2000, 2001). The account for rotation strongly favors the formation of WR stars in two ways: (1) Rotation produces mass loss enhancements according to expression (1). (2) The ro-

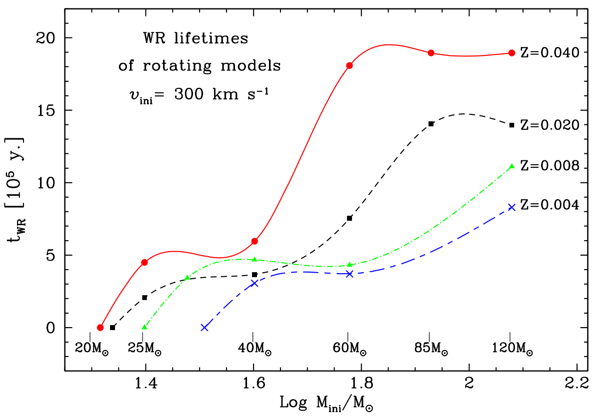

Fig. 6. WR lifetimes as a function of the initial stellar masses for rotating models at different metallicities Z.

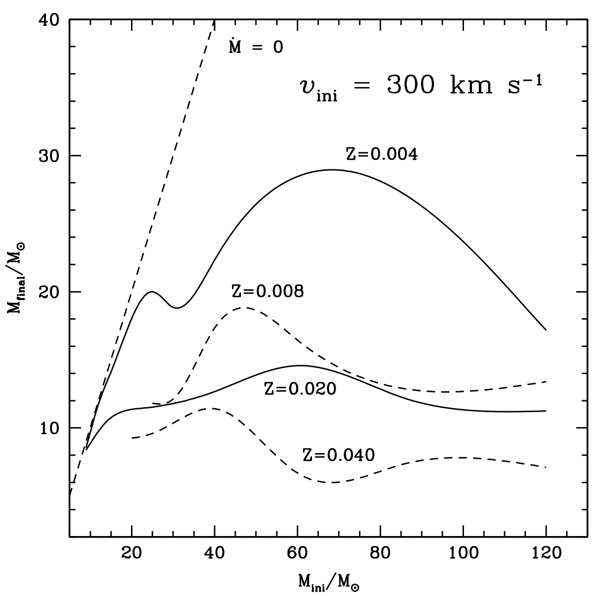

Fig. 7. Relation between the final and the initial masses for stars of different metallicity Z with account of an average rotation.

tational mixing makes the products of CNO burning, and then of 3α reaction, to appear faster at the stellar surface. Figure 6 shows the WR lifetimes for rotating models at different Z. Without rotation these curves are much lower (Meynet & Maeder 2005).

We point out that the mass–luminosity relation of WR stars without H left (types WNE and WC) well corresponds to stars at the Eddington Limit. This supports the idea that WR stars are at the Eddington Limit. If so, this has strong consequences for the mass loss rates, which should be determined by the properties of the Eddington Limit or of the $\Omega\Gamma$–Limit for rotating objects.

The comparison of the chemical compositions of WN and WC stars with the model predictions is essential. Basically, for WN stars the CNO abundances are the values of CNO nuclear equilibrium and are thus a test of nuclear reactions rather than of mixing. In WC stars, the C/He and O/He ratios correspond to partial He–burning and not to equilibrium, thus they are a strong test of mixing. In particular, the relatively low C/He ratios observed are a clear signature of mixing. Figure 7 shows the relation between the final and initial masses for rotating stars. As a result of mass loss and rotation at solar Z or higher, all massive stars finish their life with relatively low masses.

5. MASSIVE STARS AS PRECURSORS OF GRB

The explanation of the precursors of the gamma ray bursts (GRBs) is a major challenge of massive star evolution (Woosley & Bloom 2006). The critical point is that the star must loose enough mass to become a WO or a late WC star, in order to lead to a SNIc supernova with no H and no or very little He left. At the same time, the star must have kept enough angular momentum to make the collapsar model work. The major difficulty is to make a model which loses lots of mass without losing too much angular momentum.

The effects of wind anisotropies on the evolution leading to collapsars have been studied by Meynet & Maeder (2007). Rotating models of a 60 $M_\odot$ star with $\Omega/\Omega_{crit} = 0.75$ on the ZAMS, accounting for shellular rotation and magnetic field, with and without wind anisotropies, have been calculated. With the anisotropies (cf. Figure 1), a lot of mass is lost with very little angular momentum. Figure 8 shows the HR diagram of these models. In both cases, the evolution goes to the blue as a result of strong rotational mixing which produces tracks corresponding to quasi–homogeneous evolution. Wind anisotropies help maintaining a high content of angular momentum in the stellar core, while they make the star lose very large amounts of mass. The anisotropic model loses more mass than the isotropic model (cf. the much lower luminosity in Figure 8), because the anisotropic model remains near the critical limit for most of the core H-burning phase. Despite these large losses of matter, the anisotropic model ends its stellar lifetime with a high velocity, between 200–400 km s^{-1}, while the isotropic model shows very modest values (a few tenths of km s^{-1}). Only the models accounting for the effects of wind anisotropies retain enough angular momentum in their core to produce a gamma ray burst (GRB) as shown in Figure 9. The

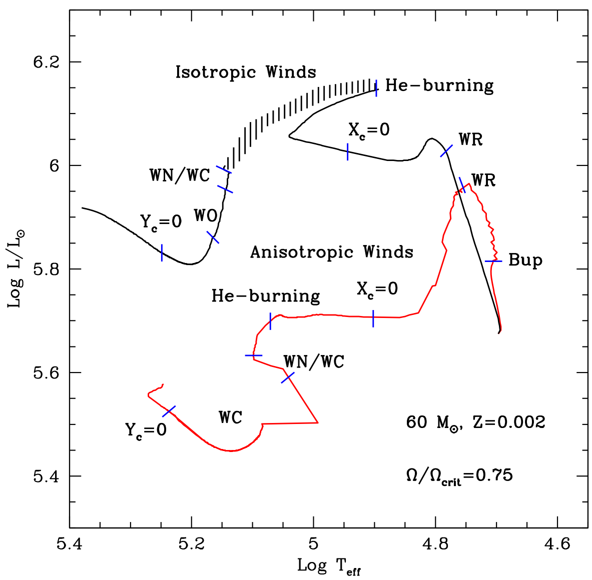

Fig. 8. Evolutionary tracks for rotating models with and without wind anisotropies. The beginning of various phases is indicated along the evolutionary sequences: "Bup, WR, and $X_c = 0$" indicate when the star encounters the break-up limit, enters the WR phase and when core H-burning stops. "He–burning" indicates the beginning of the He–burning phase. The transition WN/WC phase is shown. After that, the star is a WC star.

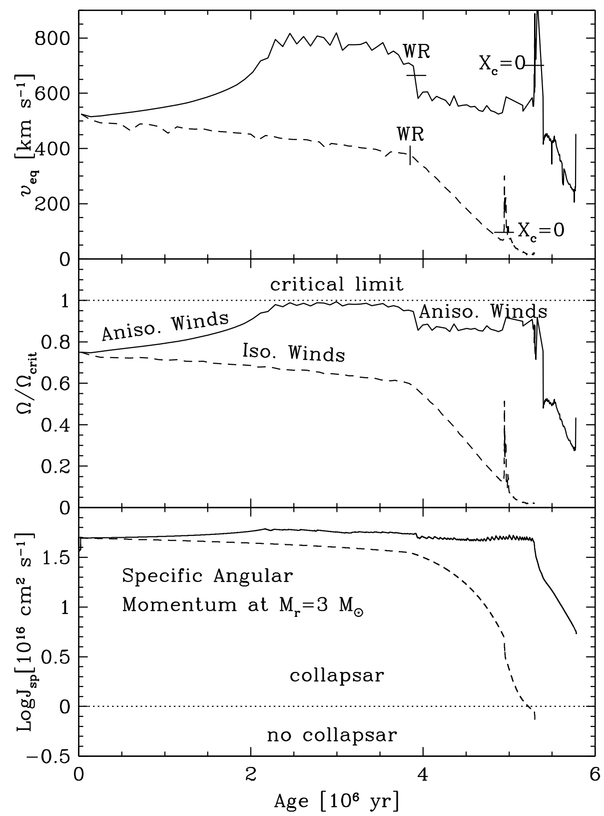

Fig. 9. Evolution as a function of time of the equatorial velocity (top) and of the ratio $\Omega/\Omega_{\mathrm{crit}}$ at the surface (middle). The bottom panel shows the evolution of the specific angular momentum at the Lagrangian mass coordinate $M_r = 3\ M_\odot$. The upper line is for anisotropic winds, the lower line is for isotropic winds. The limit below wich collapsars cannot be formed is indicated.

chemical composition is such that a type Ic supernova event occurs. Wind anisotropies thus appear to be a key physical ingredient in the scenario leading to long GRBs.

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DISCUSSION

A. Moffat - If we accept the recent results of Fullerton et al. (2006) and Bouret et al. (2005) that mass-loss rates of O-stars are ten times smaller than what they were supposed to be, what consequence would that bring in your scenario?

A. Maeder - I personally doubt about the mass loss rates may be decreased by a factor of 10 – in addition to the factor of 3 already accepted. If so, this would mean that mass loss by stellar winds as people have studied for 40 years is esentially insignificant. *Why not by the way, since we are used to stimulating revolution in our science?* However, we have to be able to explain the WR/O statistics, its Z-dependence and other data and it is far from [it] to be the case.

Jesus explains how to finely tune temperatures
for O stars...without spectra.