1. Stellar Evolution For Massive Stars

1.1. The Importance of Massive Stars

If one adopts a Salpeter IMF, there are 3 stars with $M > 8M_\odot$ for every 1000 stars with $0.1 < M < 120M_\odot$. Massive stars are very rare. But over short timescales they inject very large amounts of radiation, mass, and mechanical energy into the ISM.

Homology arguements are basically dimensional analysis of the equations of stellar structure. For high mass stars they yield $L \propto M^3$ and $R \propto M^{0.8}$, so $T_{eff} \propto M^{0.4}$. Also $T_c \propto M/R \propto M^{0.2}$. The main sequence liftime $\tau(MS) \propto M/L \propto M^{-2}$, making main sequence lifetimes of stars with $M \sim 100M_\odot$ only about 300,000 yr.

Thus a star with $M = 100M_\odot$ has $L \sim 10^6 L_\odot$. Such a star can be detected as an individual star beyond the local group even while on the main sequence.

Although few in number, about 14% of the mass of stars in a generation is in $M > 8M_\odot$. Almost all of this gets back into the ISM after stellar death; only a small amount remains locked in compact remnants (neutron stars or BH); the maximum mass of a neutron star is about 3 $M_\odot$.

Mass loss is important for massive stars. A Solar metallicity star with $M(initial) = 60M_\odot$ will lose 3/4 of its initial mass through stellar winds. For $v(wind) \sim 3000$ km/sec and $dM/dt = 4 \times 10^{-5} M_\odot$/yr, the mechanical luminosity is 30,000 $L_\odot$, or ∼10% of the star's radiative luminosity, which is $\sim 60^3$ $L_\odot$. Over a lifetime of 500,000 years, this is an energy input into the ISM of 2×10^{51} ergs. So a massive star over its lifetime injects into the ISM about the same amont of energy as does a SN.

Details of massive star evolution determine:

(a) the surface chemical composition of evolved massive stars, hence of nuclear processed material into the ISM

(b) the relative population of Wolf-Rayet stars (which are losing mass very rapidly) versus normal O type stars, and the distribution over the two types (WN vs WC) of WR stars. (The ratio n(WC)/n(WN) increases at higher metallicity.)

(c) the ratio of red vs blue supergiants

(d) the frequency of various types of core collapse SN (II - H lines present; Ib - no H lines, He lines present; Ic - no H or He features in spectra).

(e) the rotation rates of young pulsars

1.2. Consequences of zero metals

a) Star formation is affected as the metals are normally important in providing cooling during the collapse of a gas cloud into a proto-star. Details discussed in section on star formation.

b) lower opacities, especially in the UV, will tend to raise the luminosity of a massive 0Z star since

$$L(rad) \;=\; 4\pi R^2[\frac{4\pi}{3\kappa_R\rho}acT^3\frac{dT}{dr}].$$

c) Without any CNO for catylizing nuclear reactions, the CNO H-burning process cannot run. A 0Z massive star must burn H using the much slower pp chain. Since this is a slow process, but the stellar luminosity is high, the central temperature must be very high $T_c \sim 10^8$ K, to produce the required energy. To achieve such a high T_c, the star must contract, using gravitational energy to cover for its deficit of nuclear energy. The star continues gravitational contraction to a smaller radius than would occur for a star with the same mass but with Solar Z. This continues until enough ^{12}C is produced by burning He from the Big Bang via the 3α process, which will run at this high T_c, to ignite the CNO cycle of H burning.

d) With regard to stellar evolution, the lower mean atomic weight due to absence of heavy elements is insigificant. The somewhat lower He abund ($Y \sim 0.24$ vs 0.28) is not very important.

e) In late stages of stellar evolution when there is mass loss, there will be no dust in the outer layers of the stellar atmosphere and the stellar wind. Molecules will have to form in the gas phase, not on the surfaces of dust grains. Radiatively driven winds will not be as important as at higher metallicity, as it is the radiation pressure on dust (for luminous cool stars) and the line emission in atomic lines (for luminous hot stars) that normally drives such winds.

f) Ignoring the effect of rotation, given their lower mass loss rates, massive stars will end their lifetimes at higher final mass than a solar metallicity star of the same initial mass. Pair instability SN, which leave no remnant, ejecting all the star's mass into the ISM, will be more frequent at 0Z.

g) With regard to the chemical evolution of the ISM, in the Solar neighborhood we observe that $\Delta Y/\Delta Z \sim 2$. At very low metallicity, Y remains almost constant at the Big Bang value as Z steadily increases. The small increment in Y from stellar evolution over several stellar generations is very small compared to the initial Big Bang He abundance. This does not hold for heavier elements not produced in the Big Bang, hence not present at all at $Z = 0$.

The combination of an extended contraction phase and the low opacity leads to 0Z stars that are more compact, with smaller radii, than solar Z stars. A 0Z $20M_\odot$ star has a radius 3.5 times smaller than that of star with the same mass at Solar Z. A smaller radius leads to a shorter timescale to mix from center to surface for a given value of the diffusion coefficient, and to steeper gradients in angular momentum.

1.3. Detecting 0Z Massive Stars

No 0Z star has ever been confirmed through spectroscopy in our galaxy, in its halo, or in any of the nearby galaxies for which such studies are possible. The T_{eff} of 0Z stars with $M > 90M_\odot$ is predicted to be approximately constant at 10^5 K, while that of Solar metallicity stars in the same mass range is almost constant at 50,000 K. The higher T_{eff} of a 0Z star of a given mass than a MS star of the same mass with Solar metallicity, both of which have approximately the same total luminosity, means the former will emit many more ionizing photons in the UV. The 0Z massive star will ionize a much larger number of H atoms in the surrounding ISM, and produce very strong recombination lines, much stronger than for a higher metallicity star. The harder radiation field will produce intense HeII (1640 Å) emission.

A search for the intense HII regions expected from massive 0Z stars at high redshift may be possible with JWST or with the TMT. The SKA should be able to image neutral H at high redshift and track the reionization of the IGM with time. LOFAR, a proposed large array of low frequency radio detectors, is designed to carry out tomogrpahy of the redshifted HI out to $z \sim 30$, when the 21 cm spin-flip HI transition is shifted to 50 MHz. This project faces a very large sky background which will make any detection very challenging.

The fact that no star with $Z < \sim Z_\odot/10,000$ is known to date means that the early phase of 0Z stars must have been very brief or that no low mass stars were formed at that time (i.e. an IMF biased towards very high mass stars), and that Z built up to a level such that the effects described above are not relevant ($Z \sim Z_{\odot}/10^4$) quite rapidly, by redshift $z \sim 6$ or even earlier.

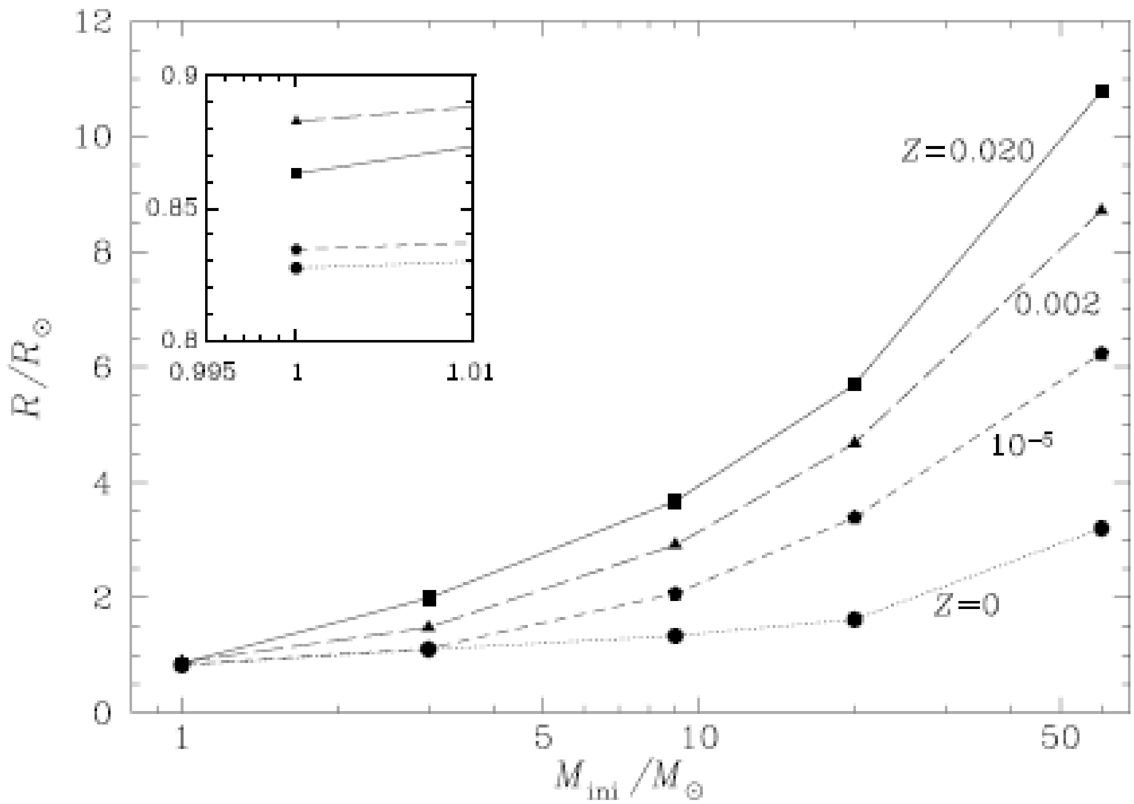

Fig. 1. Variations of the radius as a function of initial mass, for various metallicities for non-rotating stars. The inset zoom shows the small difference of radii in the case of the 1 $M_{\odot}$ models.

Fig. 1.— Fig. 1 of Ekstrom, Meynet, Maeder & Barblan, 2008, A&A, 478, 467

1.4. Mass Loss and The Role of Stellar Rotation

Mass loss in high mass stars is important. Mass loss take two forms, radiatively driven winds and mechanical winds. The former occurs through radiation pressure on dust grains in the outer part of the star's atmosphere in cool stars, and through line opacity in hotter stars, and is expected to be less important for low metallicity. The latter is an issue of whether an atom at the stellar surface is gravitationally bound is or lifted by non-gravitational effects such as radiation pressure (stellar L reaching the Eddington limit) or the centrifugal acceleration from stellar rotation. These can lower g at the stellar surface to the point where material can escape. At solar metallicity, radiatively driven winds dominate.

dM/dt depends on the stellar luminosity, the escape velocity at the stellar surface ($v_{esc} = \sqrt{2GM/R}$), and the metal abundance. Empirically there is a good correlation between $(dM/dt)v_\infty R^{1/2}$ and the stellar luminosity, where v_∞ is the wind velocity far from the stellar surface, and it is proportional to v_{esc}.

Observed mass loss rates in solar metallicity hot massive stars are 10^{-8} to 10^{-4} $M_\odot$/yr. Observations suggest $dM/dt \propto L^{1.7}$, and from homology arguements as above, $L \propto M^2$, so $dM/dt \propto M^{3.4}$. The timescale for mass loss $M/(dM/dt)$ is then proportional to $M^{-2.4}$. The result is that massive stars are affected by mass loss even on the main sequence.

Mass loss timescales decrease much faster than main sequence evolutionary lifetimes (i.e. time to burn all H in the core of the star), which are $\propto (Mc^2/L) \propto M^{-1}$. (The homology arguements given above yield $\tau(MS) \propto M^{-2}$, while a better calculation suggests that $\tau(MS) \propto M^{-0.6}$ is appropriate.)

The total amount of mass lost by such a star while on the main sequence is then $\Delta M = dM/dt \times \tau(MS) \propto M^{3.4}M^{-0.6} \propto M^{2.8}$. The fraction of the mass of a star lost during the main sequence phase is proportional to $\Delta M/M \propto M^{1.8}$. Because of this strong dependence on mass, mass loss becomes very important for high mass stars.

If high mass 0Z stars really do have very weak winds, they will not be very effective at polluting the ISM with nuclear processed materials, as most of their mass will end up in black holes. Solar metallicity high mass stars would then contribute much more effecitvely to the chemical evolution of the galaxy.

For low metallicity, stellar rotation enhances transport mechanisms between center and surface of a massive star (rotationally driven mixing via meridional currents). Partially burned material from the central regions of the star as well as angular momentum are transported to the stellar surface region by rotational mixing.

Rotation can enhance mass loss in low Z stars in two ways. The first is by reducing the effective gravity of the star as compared to one rotating slowly. The second is by increasing the opacity near the stellar surface as meridional currents bring up processed material which has higher Z from the central region of the star as well as angular momentum from the core. The enhancement factor is small for stars far from the Eddington limit, but at rotation rates approaching the critical velocity at the surface, $g(eff)$ decreases and mass loss rates can become very large. The maximum luminosity (the Eddington luminosity) is decreased through rotation, and may then become equal to the star's actual luminosity, at which point strong mass loss ensues.

Furthermore, at high rotation, as the reduction in $g(eff)$ becomes important, mass loss becomes anisotropic, depending on the angle from the axis of rotation. The stellar surface temperature then becomes non-uniform. Rotation causes $g(eff)$ to decrease more at the equator and less at the poles, but the radiative flux is higher at the poles, so detailed modeling of these anisotropies is required to predict the form of the wind anisotropy. Such anisotropies have been detected in maps of the surfaces of rapidly rotating hot stars made by long baseline visible and infrared interferometers; see Monnier, Zhao, Pedretti et al, 2007, Science, 317, 342, and also the Astro2010 white paper by Aufdenberg, Ridgway & White (Astro-ph:0905.1353).

For slowly roating MS stars, as the core contracts, the envelope expands. Local conservation of angular momentum requires the core to spin up while the envelope slows down, and the surface velocity evolves away from the critical velocity. But rotational currents in rotating massive stars couple the core to the surface, thus if there is no mass loss, the surface velocity increases with time and would approach the critical value. But when radiatively driven winds are important, angular momentum is lost from the surface to the wind, $v(rot)$ at the surface decreases with time, and the star evolves away from the critical limit.

Since there are no 0Z massive stars in existence at the present time, we do not know anything about the distribution of their initial rotational velocities. However, hot MS stars of solar metallicity do have large $v(rot)$ in many cases, and there is some evidence from studying LMC and SMC populations that $< v(rot) >$ is higher at lower metallicity. Some references re stellar rotational velocity distributions in massive main sequence stars include Huang & Gies (2009, ApJ, 683, 1045) for the Milky Way and Martayan, Zorec & Fremat (2009, Astro-ph:0809.2205) for the Large and Small Magellanic Clouds.

Heger et al (2003) show that the mode of stellar death depends on the mass of the He core at the end of their evolution. For solar metallicity stars with initial masses of 64 to 135 $M_\odot$ the expected form of stellar death is PISN. If, however, the stars in this mass range have 0Z, their mass loss rates may be quite different, and if they are large enough, even a star with an initial mass of 150 $M_\odot$ may end up with a mass too low for a PISN to occur.

Evolutionary tracks for $3 < M < 60$ $M_\odot$ for a range of metallicities from 0Z to solar and with various inital rotational velocities are given by Eckstrom et al (2008).

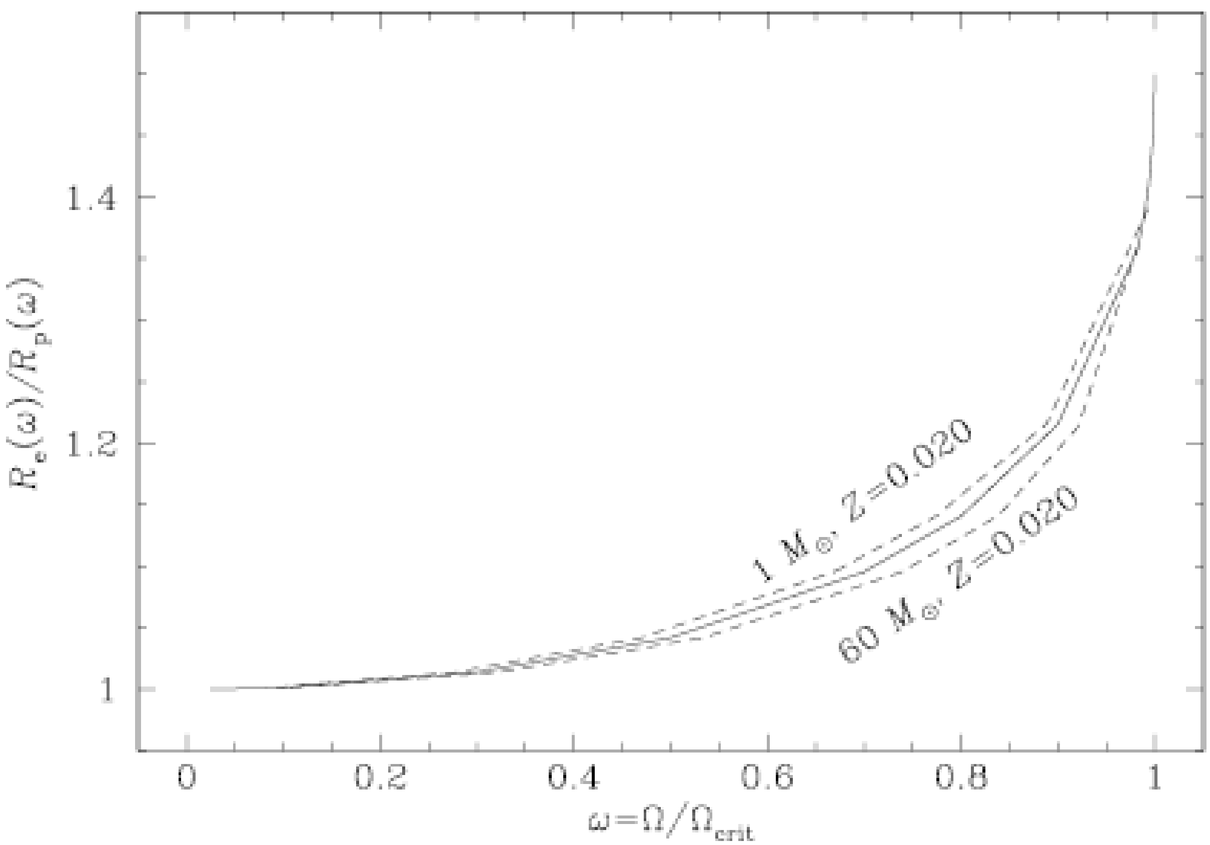

Fig. 3. Variation of the ratio $R_e(\omega)/R_p(\omega)$ (equatorial over polar radius) as a function of $\omega = \Omega/\Omega_c$. The continuous line shows the relation given by Eq. (9), assuming $R_{p,crit}/R_p = 1$. The dashed lines show the relations for the $Z = 0.020$ models with 1 and 60 $M_\odot$ using Eq. (8).

Fig. 2.— As the rotational velocity increases, the star becomes more oblate. Fig. 3 of Ekstrom, Meynet, Maeder & Barblan, 2008, A&A, 478, 467

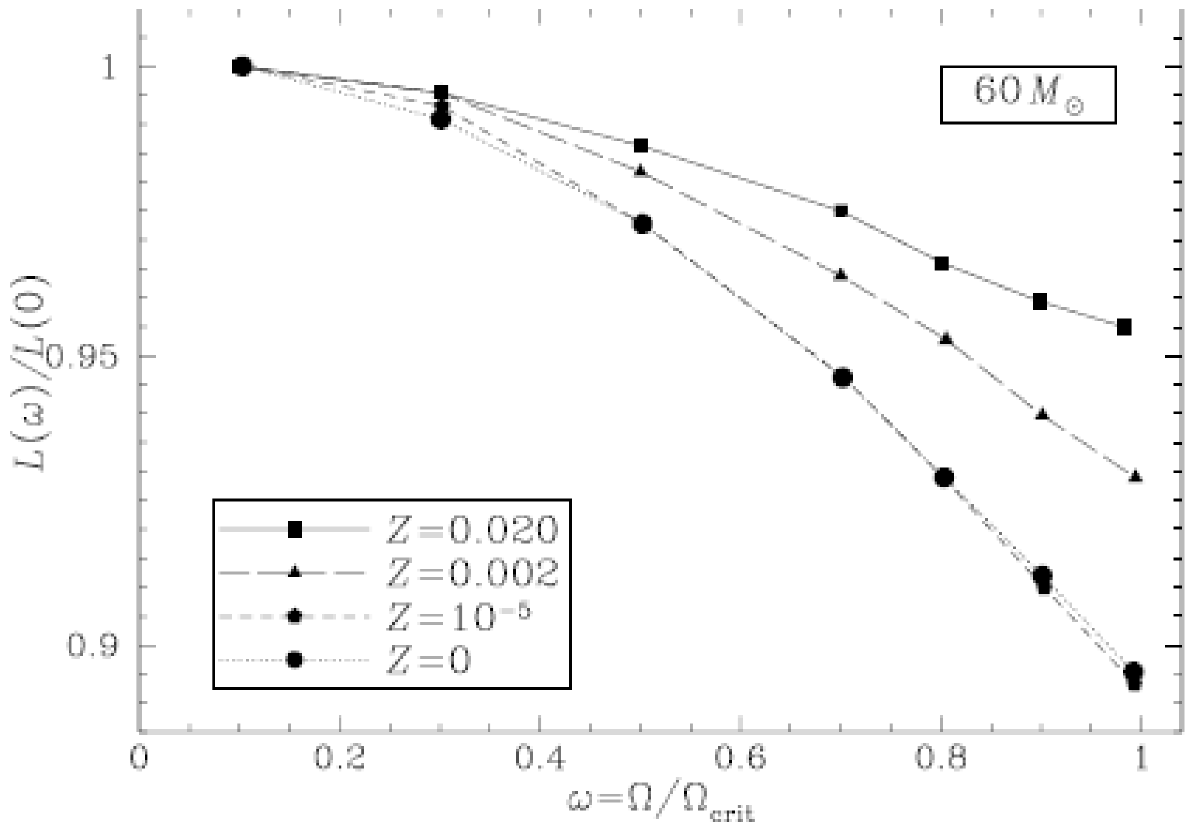

Fig. 4. Variations of the total luminosity as a function of ω, normalized to the non-rotating value, for 60 $M_\odot$ at various metallicities.

Fig. 3.— Modest change in total luminosity depending on rotational velocity. Fig. 4 of Ekstrom, Meynet, Maeder & Barblan (2008).

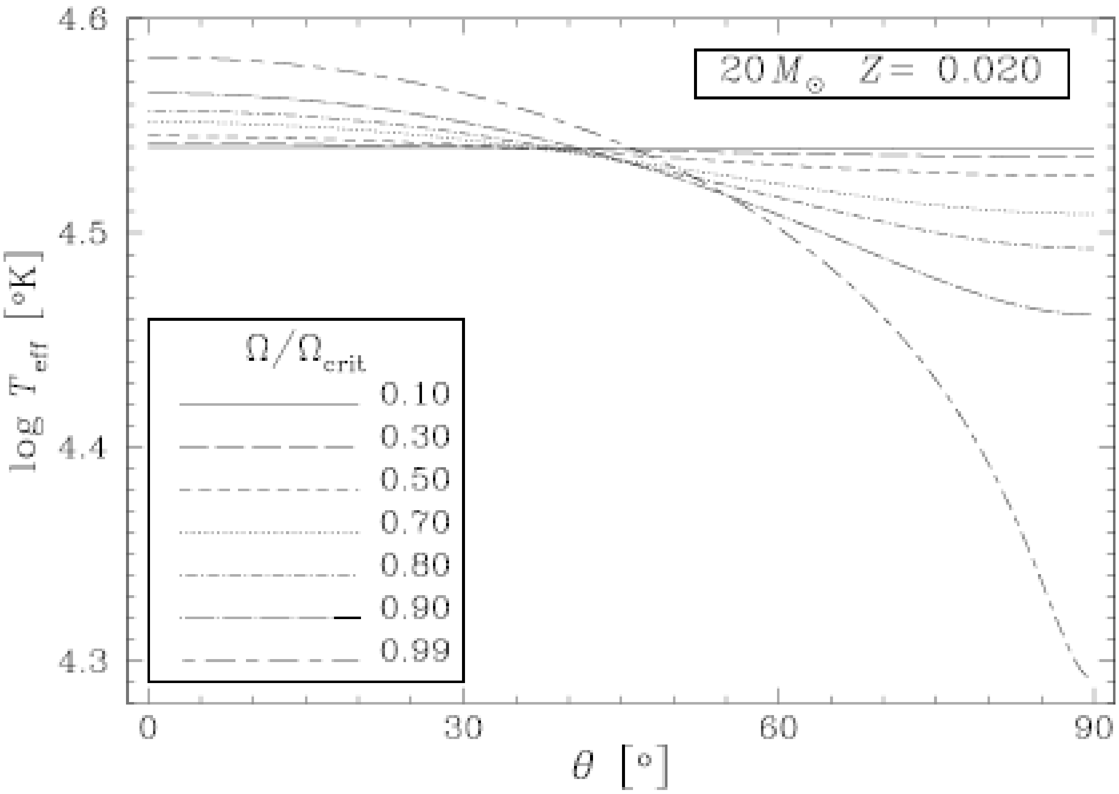

Fig. 6. Variations of the effective temperature $T_{\rm eff}$ as a function of colatitudinal angle θ, for the various values of rotational rates, in the 20 $M_{\odot}$ model at standard metallicity.

Fig. 4.— Substantial variation in T_{eff} over stellar surface for high rotational velocity. Fig. 6 of Ekstrom, Meynet, Maeder & Barblan (2008).

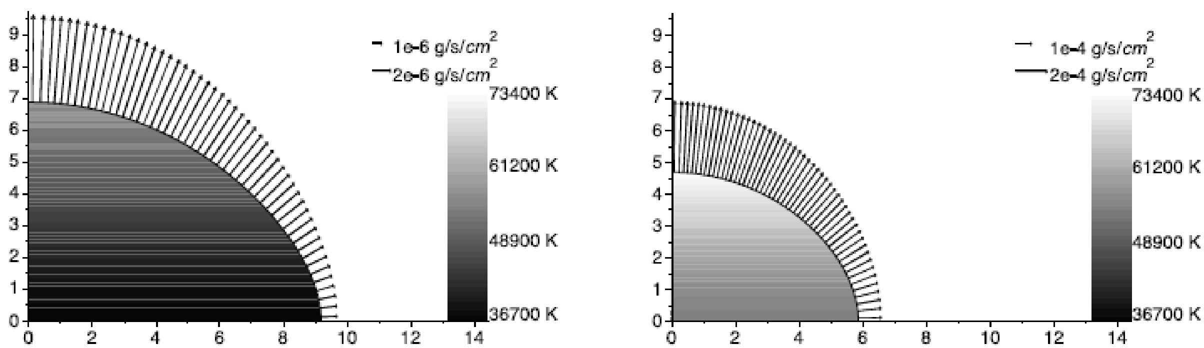

Figure 4. *Left panel*: Variation of the mass flux at the surface of an initial $35M_\odot$ at a stage during the core H-burning phase when the mass fraction of hydrogen at the centre is $X_c = 0.42$. The axis are in units of solar radius. The velocity of the star on the ZAMS is 550 km s^{-1} corresponding to $\Omega/\Omega_{\rm crit} = 0.84$. The star follows a homogeneous evolution. At the stage represented $\Omega/\Omega_{\rm crit} \sim 1$. *Right panel*: Same as the left panel, but for a later stage with $X_c = 0.02$ and $\Omega/\Omega_{\rm crit} \sim 1$. Courtesy of C. Georgy.

Fig. 5.— Mass loss rate varies over the surface of a rotating massive star. Note scale in right panel of mass loss is 100 times that of left panel. Fig. 4 of Meynet et al (2009) to IAU Symp. 250, Massive Stars as Cosmic Engines.

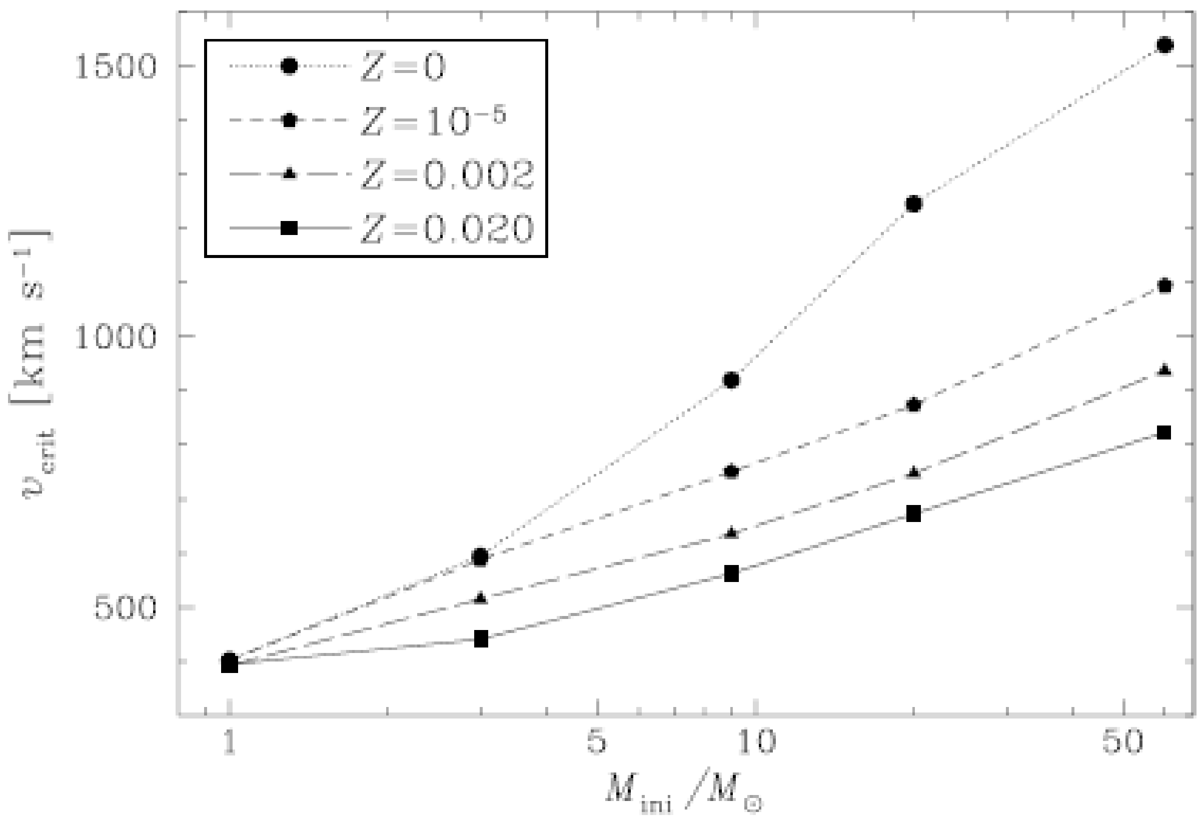

Fig. 11. Variations of the critical equatorial velocity on the ZAMS as a function of the initial mass, for various metallicities.

Fig. 6.— Fig. 11 of Ekstrom, Meynet, Maeder & Barblan (2008).

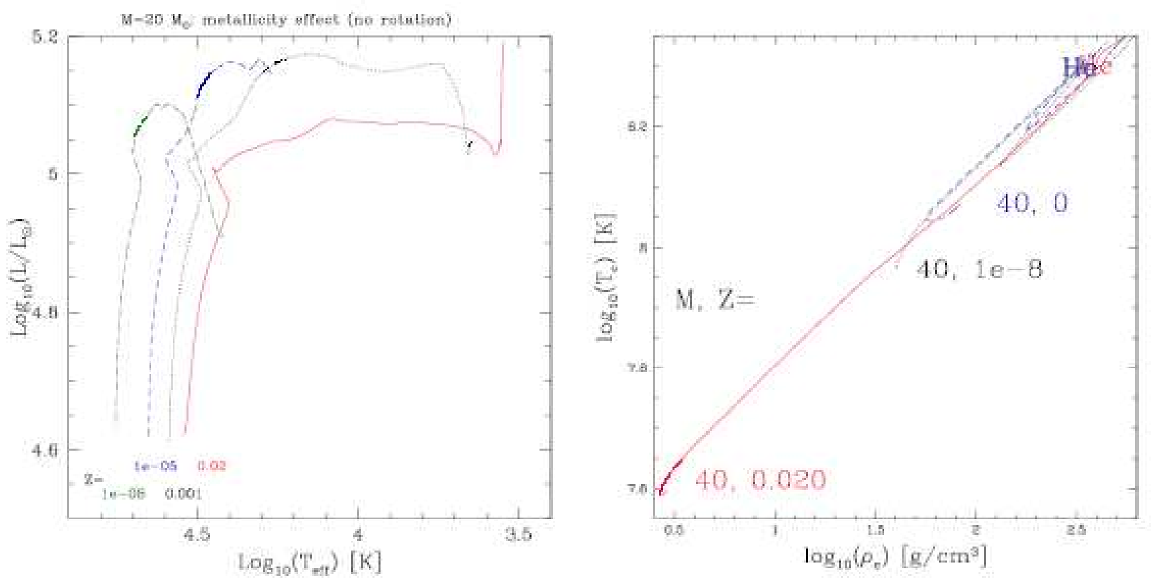

Figure 1. *Left*: H-R diagram for non-rotating 20 $M_\odot$ models with $Z = 10^{-8}, 10^{-5}, 0.001$ and 0.02, showing that more metal poor stars have more compact envelopes and are less likely to reach the red supergiant stage. *Right*: Central temperature versus central density diagram for 40 $M_\odot$ models with $Z = 0, 10^{-8}$ and 0.02. The evolutionary tracks start where hydrogen burning start and the He symbols are placed at the start of helium burning. The central conditions are much hotter and denser at very low Z. Note also the different initial H-burning conditions between $Z = 0$ and 10^{-8} (explained in the text).

Fig. 7.— (Left panel) Evolutionary tracks for non-rotating massive stars as a function of metallicity. Massive 0Z stars are much hotter on the main sequence than are Solar metallicity stars of the same mass. (Right panel) Note much higher T and ρ near center of star as Z decreases for a fixed 40 $M_\odot$ mass star. From Hirschi, Chiappini, Meynet, Maeder & Ekstrom, 2008, a conference proceedings, see arXiv:0801.1675.

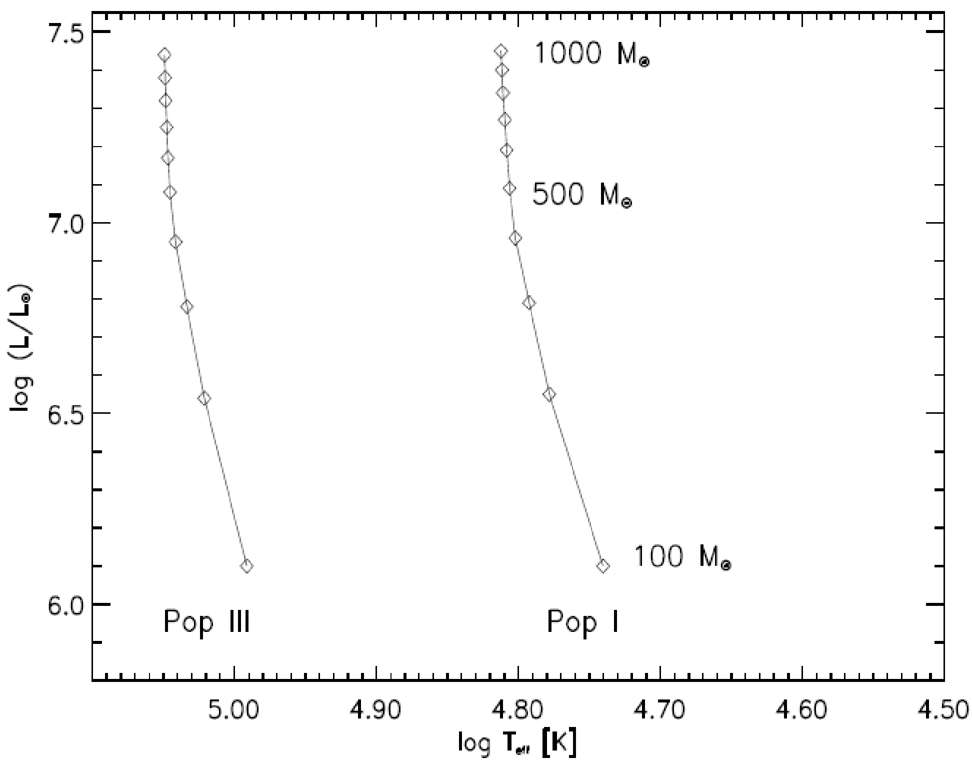

FIG. 1.— Zero-age main sequence of very massive stars. *Left solid line:* Population III zero-age main sequence (ZAMS). *Right solid line:* Population I ZAMS. In each case, stellar luminosity (in $L_{\odot}$) is plotted vs. effective temperature (in K). *Diamond-shaped symbols:* Stellar masses along the sequence, from $100M_{\odot}$ (bottom) to $1000M_{\odot}$ (top) in increments of $100M_{\odot}$. The Population III ZAMS is systematically shifted to higher effective temperature, with a value of $\sim 10^5$ K which is approximately independent of mass. The luminosities, on the other hand, are almost identical in the two cases.

Fig. 8.— Schematic main sequence evolutionary tracks for high mass 0Z stars and those of solar metallicity. Fig. 1 of Bromm, Kuritzski & Loeb, 2001, ApJ, 552, 464.

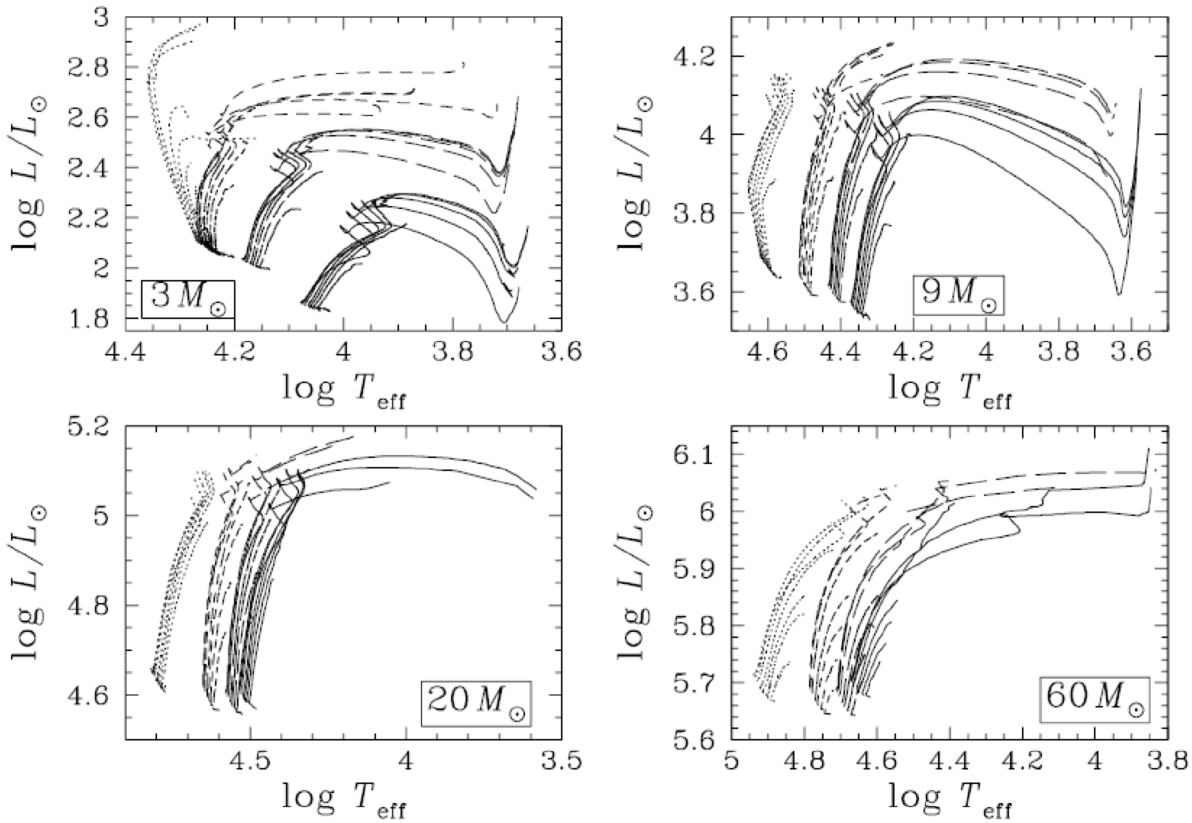

Fig. 13. Evolutionary tracks in the theoretical Hertzsprung-Russell diagrams for all the models computed beyond the ZAMS. The effective temperature corresponds to a surface averaged effective temperature. The computations are stopped when the star reaches the critical limit or before the beginning of the core He-burning phase.

Fig. 9.— Evolutionary tracks for various metallicity stars. Line types denote metallicity as in Ekstrom et al, fig 11. Fig. 13 of Ekstrom, Meynet, Maeder & Barblan (2008).

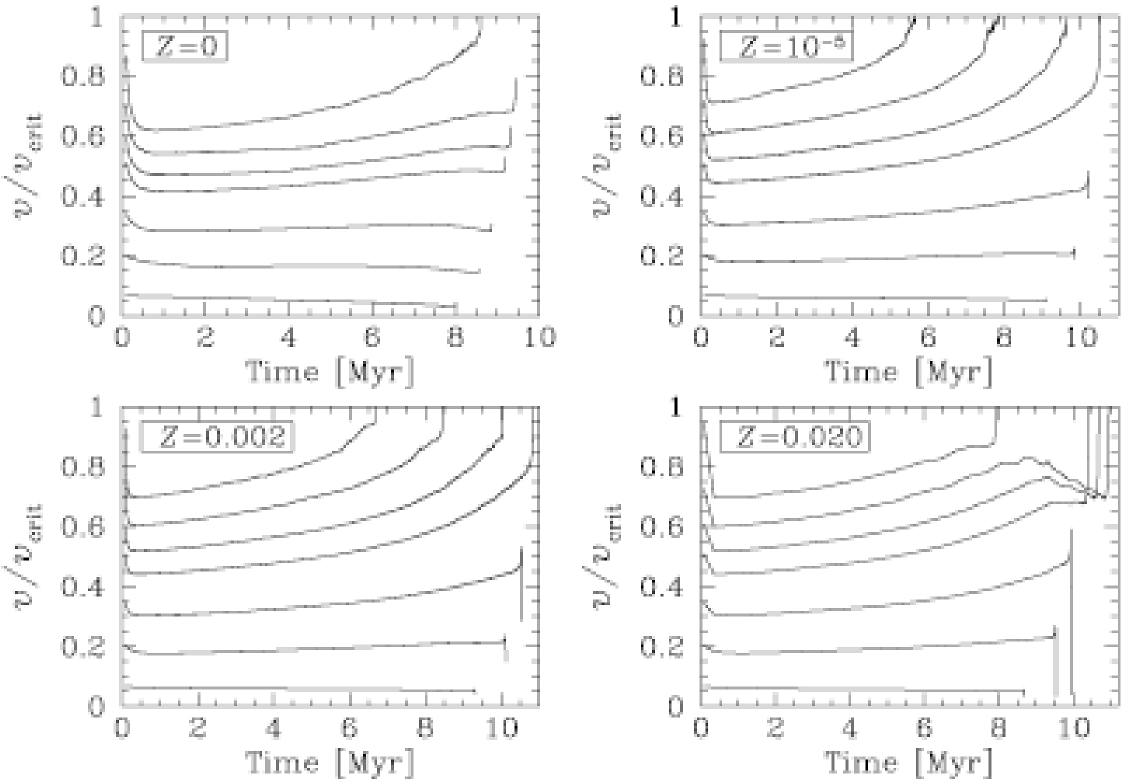

Fig. 15. Evolution of the ratio $v/v_{\rm crit}$ during the core hydrogen-burning phase for the 20 $M_{\odot}$ models at various metallicities. The computations were stopped as soon as the star reaches the critical limit or just before the beginning of the core He-burning phase.

Fig. 10.— Lines that end at $v/v_{crit} = 1$ denote stars that suffer enormous mechanical mass loss while still burning H. Fig. 15 of Ekstrom, Meynet, Maeder & Barblan (2008).

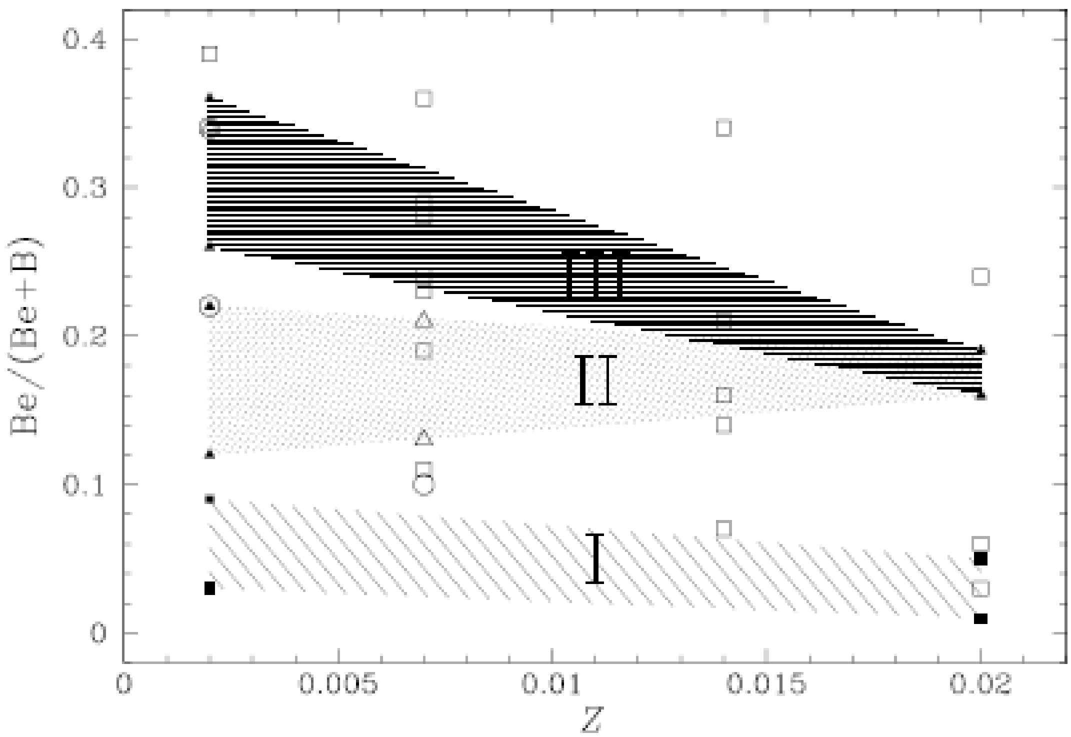

Fig. 22. The empty symbols correspond to the observed fraction of Be stars among B0-B3 type objects in clusters with ages ranging from 10 to 25 Myr. Data are taken from Wisniewski & Bjorkman 2006 (circles), Keller et al. 1999 (triangles) and Maeder et al. 1999 (squares). The filled symbols correspond to predictions of the given models for $Z = 0.002$ and $Z = 0.020$ and for ages equal to 10 and 25 Myr respectively (we estimated the fraction of Be in a two magnitude interval below the turn off, as did Maeder et al. 1999). The hatched zone labelled by I correspond to stars predicted at the critical limit. The hatched zone labelled by II shows the fractions of stars with $\upsilon/\upsilon_{\rm crit} \geq 0.7$. These two cases were obtained assuming a velocity distribution of Huang & Gies (2006a). The third hatched region, labelled III corresponds to stars with $\upsilon/\upsilon_{\rm crit} \geq 0.7$ and assuming that at low metallicity the initial distribution of rotation contains faster rotators (see text).

Fig. 11.— Comparison of observed and predicted ratios of Be stars to all B stars in young open clusters. Be stars are presumably the fast rotators. Fig. 22 of Ekstrom, Meynet, Maeder & Barblan (2008).

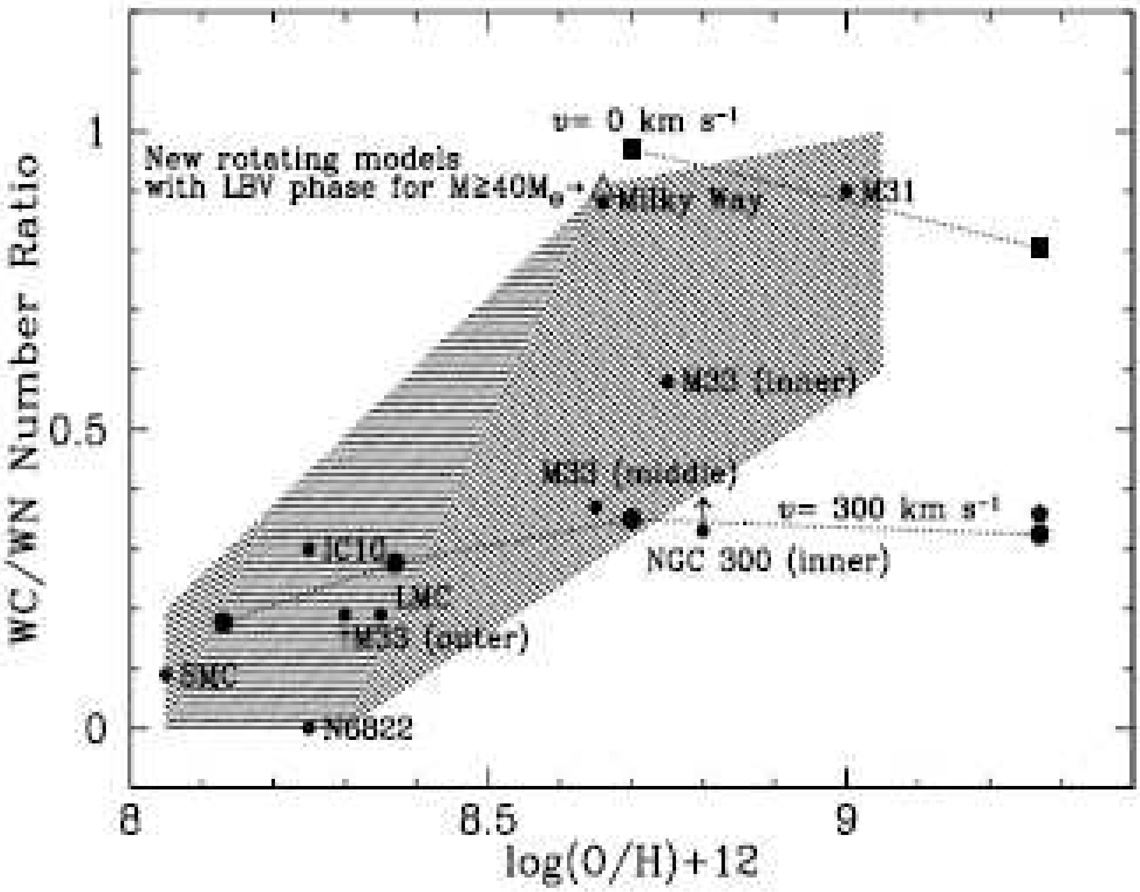

Fig. 12.— Predictions for ratio of WN to WC Wolf-Rayet stars as a function of metallicity compared to mean observed ratio for various nearby galaxies. Fig. 4 of Meynet et al (2009), IAU Symp. 250, Massive Stars as Cosmic Engines.

Suggested reading:

a) First Light (Saas-Fe Advanced Course 36), chapter by A. Loeb

b) Bromm & Larson, 2004, ARAA, 42, 79

c) Evolution of massive stars along cosmic history, Meynet, Ekstrom, 2008, A&A, 478, 467 and more recent conference contributions, see especially proceedings of IAU Symposium 250, Massive Stars as Cosmic Engines.

d) Gregory, Chiappini & Maeder, Reviews Modern Astronomy, 21, 2009

e) Heger, Fryer, Woosley, Langer, Hartmann, 2003, ApJ, 591, 288 stellar death channels for non-rotating massive single stars

f) Ekstrom, Meynet, Chiappini, Hirschi & Maeder, 2008, A&A, 489, 685 and Ekstrom, Meynet, Maeder & Barblan, 2007, Astro-ph:0711.1735