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THE EVOLUTION OF VERY MASSIVE STARS

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ABSTRACT

Core collapse of dense massive star clusters is unavoidable, and this leads to the formation of massive objects, with masses of up to 1000 $M_\odot$ and even larger. When these objects become stars, stellar wind mass loss determines their evolution and final fate, and decides on whether they form black holes (with normal mass or with intermediate mass) or explode as a pair-instability supernova. In this paper we discuss the evolution of very massive stars and present a convenient evolution recipe that can be implemented in a gravitational *N*-body code to study the dynamics of dense massive clusters.

Subject headings: stars: evolution — stars: winds, outflows — supergiants

1. INTRODUCTION

The inner 100 pc of the Galactic center contains several young dense star clusters (Figer et al. 1999a), some of them with reliable mass estimates (Borissova et al. 2005). Of particular interest are the Arches cluster (Figer et al. 2002), the Quintuplet cluster (Figer et al. 1999b), IRS 13E (Maillard et al. 2004), and IRS 16SW (Lu et al. 2005). Gravitational *N*-body simulations reveal that soon after birth such clusters may experience core collapse in which, depending on the initial cluster radius, many or most of the massive stars participate in a "collision runaway" or "collision merger" (Quinlan & Shapiro 1990; Portegies Zwart et al. 1999; Figer & Kim 2002; Gürkan et al. 2004; Gürkan & Rasio 2005; Freitag et al. 2006). In a recent paper, Portegies Zwart et al. (2006) estimated the typical mass of these objects. They concluded that clusters in the inner 10 pc (respectively between 10 and 100 pc) of the Galactic center form collision mergers with an average mass $\approx$1000 $M_\odot$ (respectively $\approx$500 $M_\odot$). The dynamical evolution of a cluster where core collapse happens obviously depends on whether or not the very massive merger becomes a very massive star and, when a very massive star is formed, on the evolution of this very massive star.

The present paper deals with the evolution of very massive stars, products of runaway merging. The computation method is outlined in § 2, where we provide an easy evolution calculation recipe. It is obvious that this evolution is critically affected by stellar wind mass loss. The formalism that we use is discussed in § 3. The evolution of stars with a postmerger mass between 300 and 1000 $M_\odot$ is illustrated in § 4.

2. SIMULATING THE EVOLUTION OF VERY MASSIVE STARS

In the subphotospheric layers of very massive stars, where the opacity becomes larger than the electron scattering value, the radiation force almost balances gravity, causing a core/extended halo stellar structure. This hampers the convergence of stellar evolutionary computations. However, since the mass of these layers is very small, they hardly affect the overall internal structure and treating these layers using Thomson scattering opacity only, still provides an accurate description of very massive stellar evolution while at the same time avoiding any numerical difficulties.

Our calculations of the evolution of very massive stars are based on the results of Nadyozhin & Razinkova (2005, hereafter NR05), who constructed interior models for massive objects using the similarity theory of stellar structure (treated as a boundary-value problem). Their models correspond to chemically homogeneous stars, having Thomson scattering as the only opacity source throughout. The obtained model sequences depend on one parameter only; $\mu^2 M$ (μ being the mean molecular mass of the gas and M the total mass of the star). During most of their evolution very massive stars produce a convective core that almost covers the entire star, meaning that their evolution can be simulated accurately with a homogeneous model. The fact that very massive stars are expected to lose a significant amount of mass by stellar wind (§ 3) strengthens the conclusion that very massive stars evolve in a quasi-homogeneous way. Furthermore, in cases of steep dependencies of the energy generation rate on temperature (as is the case for the CNO cycle and the 3α-reaction), most of the energy production is localized near the very center of the star. Therefore, to a very good approximation, the luminosity is constant throughout the star and the dimensionless luminosity equation is decoupled from the rest of the stellar structure equations. This means that the model sequence of NR05 can be used to describe the core hydrogen burning (CHB), as well as the core helium burning (CHeB) stage of very massive stars.

To simulate the evolution of a star, we proceed as follows. NR05 provide best-fit relations (see their eqs. [30], and [34] in combination with [36]) as a function of $\mu^2 M$ for the luminosity and convective core mass of their computed sequence (which covers the range $0 < \mu^2 M \leq 4000\ M_\odot$). For a given stellar luminosity (and assuming that central nuclear burning is the only energy source in the star), conservation of energy allows one to derive the amount of nuclear fuel that is burned per unit of time. Then, from knowledge of the size of the convective core, a differential equation for the variation of the central abundance of the fuel is obtained. For the CHB case, we have

$$M_{\rm cc}(\mu, M)\frac{dX}{dt} = -\frac{L(\mu, M)}{\epsilon_{\rm H}}, \qquad (1)$$

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where ϵ_H is the energy produced from burning one mass unit of hydrogen. In this equation, both M_{cc} and L vary due to changes not only of μ, but also of M through stellar wind mass loss:

$$\frac{dM}{dt} = \dot{M}(\mu, M, L). \quad (2)$$

Assuming the mass-loss rate $\dot{M}$ can be derived from knowledge of μ, M, and/or L, the solution of this coupled set of two differential equations provides the evolution of the quantities X, μ, M, M_{cc}, L and $\dot{M}$ as a function of time, as well as the duration of the hydrogen burning stage (which ends, of course, when $X = 0$).

For the CHeB case, one needs to account for the fact that C and O are produced in a nonconstant ratio, which affects the energy production per unit mass of burned helium. The equivalent of equation (1) for helium burning is (see also Langer 1989b)

$$M_{cc}(\mu, M)\left(\frac{B_Y}{A_Y}\frac{dY}{dt} + \frac{B_C}{A_C}\frac{dC}{dt} + \frac{B_O}{A_O}\frac{dO}{dt}\right) = -L(\mu, M). \quad (3)$$

In equation (3), the B symbols represent the binding energies of the corresponding nuclei whereas the A symbols are their atomic weights. We impose the additional constraint $Y + C + O = 1$ and thus $dY + dC + dO = 0$, for simplicity.

Langer (1989a) computed models for massive homogeneous CHeB stars and found an abundance evolution of C and O relative to He that was closely followed by all models ($15\ M_\odot \leq M \leq 100\ M_\odot$), independent of initial mass. This resulted in a fit between C and Y (his eq. [1]; see also his Fig. 1). According to Langer, this fit is very accurate for Y values larger than about 0.5, when the O abundance is low and the $^{12}C(\alpha, \gamma)^{16}O$ reaction is relatively unimportant. At lower values of Y, this reaction and the fact that some ^{16}O is converted into ^{20}Ne toward the end of CHeB of very massive stars produce an estimated uncertainty in the fit of about 5%–10%. Using this $C(Y)$ relation and eliminating the C and O time derivatives from equation (3), one finally obtains

$$M_{cc}(\mu, M)\left[\left(\frac{B_Y}{A_Y} - \frac{B_O}{A_O}\right) + \left(\frac{B_C}{A_C} - \frac{B_O}{A_O}\right)C'(Y)\right]\frac{dY}{dt} = -L(\mu, M). \quad (4)$$

Here $C'(Y)$ denotes the derivative of the $C(Y)$ fit of Langer, with respect to Y. As was the case for H burning, the combination of equation (4) with a mass-loss rate formalism of the form of equation (2) enables one to compute the evolution of the star up to He depletion in the core.

In § 4 we compare evolutionary results of massive stars, which are calculated with the similarity theory with results calculated with detailed stellar evolutionary codes in order to evaluate our computational method.

3. THE STELLAR WIND MASS-LOSS FORMALISM OF VERY MASSIVE STARS

Since direct observations of very massive stars in general and their stellar wind mass-loss rates in particular are lacking, we are forced to estimate the effect of stellar wind mass loss on very massive star evolution either by extrapolating empirical formalisms holding for massive stars or by using theoretical models when they are available. Kudritzki (2002) studied line-drive winds of very massive stars and calculated mass-loss rates as function of metallicity Z of very massive O-type stars with a luminosity $\log L/L_\odot$ between 6.3 and 7.03 and for T_{eff} values between 40,000 and 60,000 K, and he presented $\dot{M}$-interpolation formulae for three different T_{eff} values. Notice that the mass-loss rates are smallest for the highest T_{eff}. This means that if, by using the $\dot{M}$-interpolation formula corresponding to the highest T_{eff} during the whole CHB phase, we predict that stellar wind mass loss of very massive stars is large, the real mass loss may be even larger.

Due to stellar wind mass loss during CHB, the post-CHB (CHeB) remnants of the very massive stars are hydrogen deficient and may be considered as very massive Wolf-Rayet (WR) stars, e.g., the evolution of very massive stars during CHeB has to be calculated accounting for WR-like mass-loss rates. Theoretical formalisms have been presented by Nugis & Lamers (2002), but they contain stellar wind parameters that can only be derived by linking a full hydrodynamical wind model to a stellar evolutionary model (e.g., the temperature and radius in the wind at the sonic point, the wind velocity at infinity.). Therefore, we prefer to rely on empirical formalisms. Based on indirect arguments involving population synthesis of WR stars in the solar neighborhood (the WN/WC number ratio), on the masses of black holes in binaries, and on direct mass-loss rate determinations of WR stars including the effects of clumping (before 1998 the effects of clumping on empirical mass-loss rates was investigated for only a few WR star), Vanbeveren et al. (1998; see also Van Bever & Vanbeveren 2003) proposed the following relation:

$$\log(\dot{M}) = \log(L) - 10 + 0.5\log(Z/Z_\odot), \quad (5)$$

where Z stands for the *initial* metallicity which is proportional to the Fe abundance of the WR star.

Nugis & Lamers (2000) used clumping-corrected mass-loss rates of a large sample of Galactic WR stars and proposed the following $\dot{M}$ formula as function of luminosity and helium abundance Y,

$$\log(\dot{M}) = -11 + 1.29\log(L) + 1.7\log(Y) + 0.5\log(1 - X - Y). \quad (6)$$

In the two formulae given above $\dot{M}$ is in $M_\odot\ yr^{-1}$ and L in $L_\odot$.

Remarks.—Kudritzki (2002) calculated the mass-loss rates for stars with a luminosity $\log(L/L_\odot)$ up to 7. Initially (on the zero-age main sequence) our $1000\ M_\odot$ star has $\log(L/L_\odot) = 7.5$ and we extrapolated the $\dot{M}$-interpolation formulae. We obviously assured that the mass-loss rates in the extrapolation zone are smaller than or equal to the maximum mass-loss rates for line driving as discussed by Owocki et al. (2004).

The WR stars where both empirical WR mass-loss rate formulae given above hold, have luminosities in the range $5.0 \leq \log L \leq 6.0$. The theoretically predicted very massive WR stars (§ 4) have luminosities up to $\log L = 7$. The very massive WR mass-loss rates that we use here are therefore extrapolated values implying quite some uncertainty. In the next section we will discuss the consequences of this uncertainty. Similarly as for the CHB mass-loss rates it is obvious that also here we check that the extrapolated values remain smaller than or equal to the maximum rates.

4. RESULTS

In order to illustrate to what extent our very massive star evolutionary scheme approaches detailed evolutionary computations, Table 1 compares the $120\ M_\odot$ evolutionary result of Schaller et al.

TABLE 1

Comparison of Massive and Very Massive Star Evolutionary Computations

$M_{\rm init}$	Z	$M_{\rm e\,CHB}$	$T_{\rm CHB}$	$M_{\rm eWR}$	$T_{\rm CHeB}$	Reference
1000.........	2.10^{-6}	466.76	2.050	415.18	2.31	This paper
		482	1.861	419	2.15	Marigo et al. (2003)
120...........	0.02	69.64	2.753	7.91	4.65	This paper
		70.28	2.611	7.77	4.40	Schaller et al. (1992)

Notes.— Performed with a detailed evolutionary code and with the similarity method used in the present paper. All masses are in $M_\odot$, $T_{\rm CHB}$ is in Myr, and $T_{\rm CHeB}$ is in 10^5 yr.

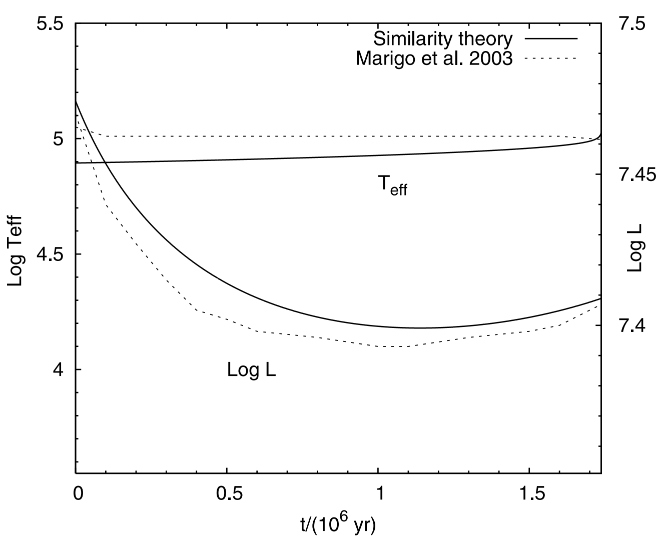
(1992) with our prediction where we obviously used the same mass-loss prescription during CHB and during CHeB as in Schaller et al. As can be noticed, the correspondence is very good. The basic assumption of our method is the quasi-homogeneous evolution of very massive stars. The more massive a star, the larger is the convective core and the larger is the stellar wind mass-loss rate. This means that the more massive a star the closer its evolution will be to the quasi-homogeneous one. Since our method gives very satisfactory results already for the 120 $M_\odot$ star, we are inclined to conclude that it will closely describe the evolution of very massive stars. The latter is strengthened by the following. Marigo et al. (2003) calculated the evolution of a 1000 $M_\odot$ zero-metallicity star that is subject to a large stellar wind mass loss (they also use the Kudritzki formalism). In Table 1 we also compare the results of Marigo et al. with ours, whereas Figure 1 compares the temporal behavior of the mass of the convective core, the luminosity and the effective temperature. As can be noticed, the correspondence is excellent.

We calculated the evolution of stars with a mass in the range 300–1000 $M_\odot$ for three metallicities, $Z = 0.04$, $Z = 0.02$, and $Z = 0.001$, using the core hydrogen burning $\dot{M}$ interpolation formulae corresponding to the highest $T_{\rm eff}$ (§ 3). The collision of massive stars in a dense cluster happens typically 1 or 2 Myr after their formation. The central hydrogen abundance of the stars at the moment of collision may be significantly smaller than the initial value, which implies that even when the merger product is well mixed and becomes homogeneous, the new X may be significantly smaller than the initial value of the cluster. For this reason we performed evolutionary calculations of very massive stars with $X = 0.68$, 0.6, and 0.5. The results are summarized in Table 2, the initial mass-final mass relationship is depicted in Figure 2 (in this figure we also plot the relation for stars with initial mass smaller than 100 $M_\odot$, taken from Van Bever & Vanbeveren, 2003), the temporal evolution of the stellar mass is shown in Figure 3 and the evolutionary behavior in a mass-luminosity diagram is given in Figure 4. They illustrate the following conclusions:

1. Very massive stars with $Z \geq 0.02$ and with initial mass $\geq$ 300 $M_\odot$ lose most of their mass in the form of stellar winds during CHB and CHeB. The same applies for very massive stars with $Z = 0.001$ and with initial mass $\geq$ 500 $M_\odot$.
2. The final masses at the end of CHeB calculated with the WR mass-loss rate formulae (5) and (6) are very similar.
3. All the very massive stars with the same initial chemical composition and with an initial mass $\geq$ 300 $M_\odot$ end their life as stars with very similar final mass and their CHB and CHeB lifetimes are very similar. This is the reason why in Table 2 we only give the details for the 300 $M_\odot$ and 1000 $M_\odot$ stars.
4. A very massive star with a lower initial X has a shorter CHB lifetime, but a larger luminosity, thus a higher stellar wind mass-loss rate. This explains why the final masses for very massive stars with the same initial metallicity Z hardly depend on the initial X.
5. Very massive OB-type stars with $Z \geq 0.02$ and WR stars with $Z \geq 0.001$ obey a very tight mass luminosity relation, i.e.,

$$\log(L) = 1.07[\log(M)]^2 - 4.62\log(M) + 11.8, \quad Z = 0.04, \tag{7}$$

$$\log(L) = 1.12[\log(M)]^2 - 4.98\log(M) + 12.4, \quad Z = 0.02, \tag{8}$$



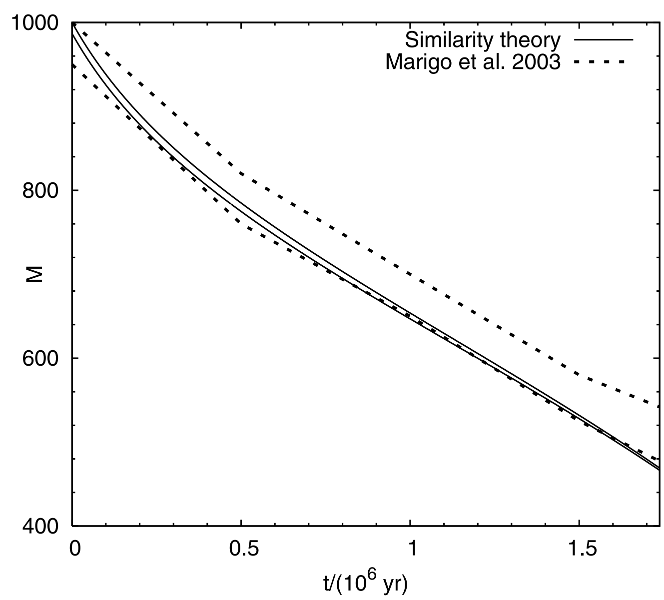


Fig. 1.—*Left:* The temporal behavior of the luminosity (in $L_\odot$) and of $T_{\rm eff}$ during CHB of a zero-metallicity 1000 $M_\odot$ star: a comparison between the results of Marigo et al. (2003) (*dashed lines*) and our method (*solid lines*). *Right:* Same as the left panel, but for the total mass (*top lines*) and the mass of the convective core (*bottom lines*). Masses are in $M_\odot$.

TABLE 2

EVOLUTIONARY PROPERTIES OF VERY MASSIVE STARS AS A FUNCTION OF INITIAL CHEMICAL COMPOSITION (Z, X)

M_{init}	Z	X	M_{eCHB}	T_{CHB}	M_{eCHeB}	T_{CHeB}
1000	0.04	0.68	140.09	2.045	22.31 (54.79, 87.12)	3.34 (2.95, 2.83)
		0.60	141.64	1.724	22.54	3.33
		0.50	144.35	1.353	22.95	3.31
	0.02	0.68	152.91	2.017	40.72 (78.37, 109.06, 35.45)	3.03 (2.83, 2.76, 3.36)
		0.60	154.56	1.701	41.19	3.02
		0.50	157.35	1.337	41.86	3.01
	0.001	0.68	220.93	1.903	163.13	2.62
		0.60	222.47	1.610	164.41	2.61
		0.50	225.15	1.272	166.42	2.61
300	0.04	0.68	136.85	2.131	21.86 (53.61, 85.14)	3.36 (2.96, 2.84)
		0.60	138.37	1.786	22.54	3.33
		0.50	140.95	1.394	22.95	3.31
	0.02	0.68	148.76	2.109	39.77 (76.30, 106.09, 34.86)	3.04 (2.84, 2.77, 3.38)
		0.60	150.20	1.769	40.05	3.04
		0.50	152.74	1.382	40.69	3.03
	0.001	0.68	205.96	2.038	152.15	2.64
		0.60	207.30	1.710	153.09	2.64
		0.50	209.63	1.337	154.96	2.63

NOTES.—We list the mass at the end of CHB (M_{eCHB}), the CHB timescale (T_{CHB}), the mass at the end of CHeB (M_{eCHeB}), and the CHeB timescale (T_{CHeB}). The CHeB numbers are always calculated using the WR mass-loss rate formula (5). For $Z = 0.04$, $Z = 0.02$, and $X = 0.68$ we also list in parentheses the two CHeB parameters using WR mass-loss rate formula (5) divided by 2 and using formula (5) divided by 4. For $Z = 0.02$ and $X = 0.68$, the third number in the parentheses corresponds to the case where the WR mass-loss rate is computed with formula (6). All masses are in $M_\odot$, T_{CHB} is in Myr, T_{CHeB} is in 10^5 yr.

for the OB stars, and

$$\log(L) = 1.23 \log(M) + 4.19, \quad Z = 0.04, \qquad (9)$$

$$\log(L) = 1.14 \log(M) + 4.37, \quad Z = 0.02, \qquad (10)$$

$$\log(L) = 0.88 \log(M) + 4.98, \quad Z = 0.001, \qquad (11)$$

for the WR stars. All relations have a determination coefficient $R^2 \geq 0.99$.

6. When Z is larger than or equal to 0.02 our computations reveal that the very massive stars will end their life as a ≤ 40–$50\ M_\odot$ black hole. Since the Galactic bulge has such a large Z, intermediate-mass black holes with a mass of a few 100 $M_\odot$ may be difficult to form there.

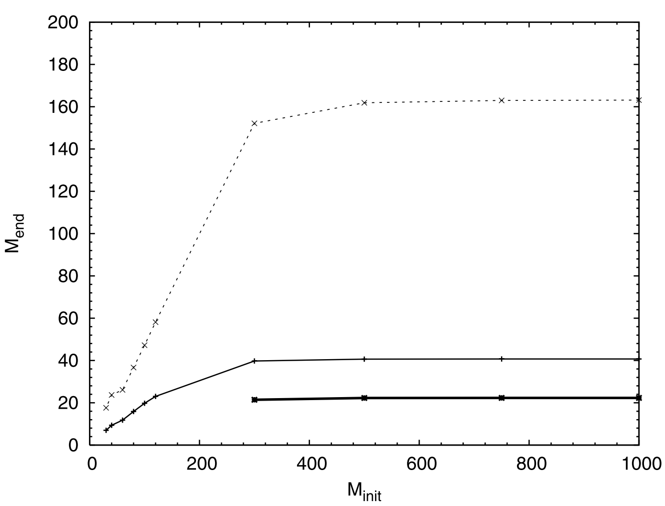


FIG. 2.—Initial mass (M_{init})-final mass (M_{end}) relation (all masses are in $M_\odot$) for $Z = 0.04$ (*thick line*), $Z = 0.02$ (*thin line*), and $Z = 0.001$ (*dotted line*).

7. For $Z = 0.001$ the final mass of very massive stars $\leq 170\ M_\odot$. Therefore, intermediate-mass black holes (but with a mass of a few 100 $M_\odot$) may form in dense metallicity poor clusters.

8. From the results of Heger & Woosley (2002), we conclude that when Z is between 0.001 and 0.02, one may expect pair-instability supernova candidates among collision runaway mergers in clusters in the Galactic center.

Remarks.—The evolutionary computations discussed above let us conclude that it may be difficult to form intermediate-mass black holes by means of runaway merging in dense clusters in the Galactic bulge (where $Z \geq 0.02$). Of course the computations rely on the adopted mass-loss rate formalisms. During CHB we used the theoretically calculated $\dot{M}$-interpolation formula corresponding to the highest T_{eff} values, which means that in reality the overall mass that is lost during CHB may be larger than the values in Table 2. Note that Kudritzki (2002) calculated the mass-loss rates of radiation driven stellar winds. Additional processes (such as rotation for example) will increase the derived rates. Furthermore, very massive stars may experience a luminous blue variable (LBV) phase somewhere near the end of CHB, much like the massive stars do. The LBV phase is characterized by eruptive (explosive; Smith & Owocki 2006) mass-loss episodes (as observed in η Car) and this may increase the total mass loss. The remarks discussed above strengthen the main thesis of the present paper.

A major uncertainty is obviously the (extrapolated) empirical WR mass-loss rate formalism for the very massive stars. To illustrate the importance of this uncertainty we computed the evolution of the very massive stars ($Z \geq 0.02$) but with WR mass-loss rates which are a factor 2 and 4 smaller than predicted by the relations given in § 3. The results are given in Table 2 as well. As expected, the final CHeB masses are larger and some of them fall in the range where we expect pair-instability supernovae to happen, e.g., these stars do not form BHs at all. Since a pair-instability supernova happens roughly when the final CHeB mass is larger

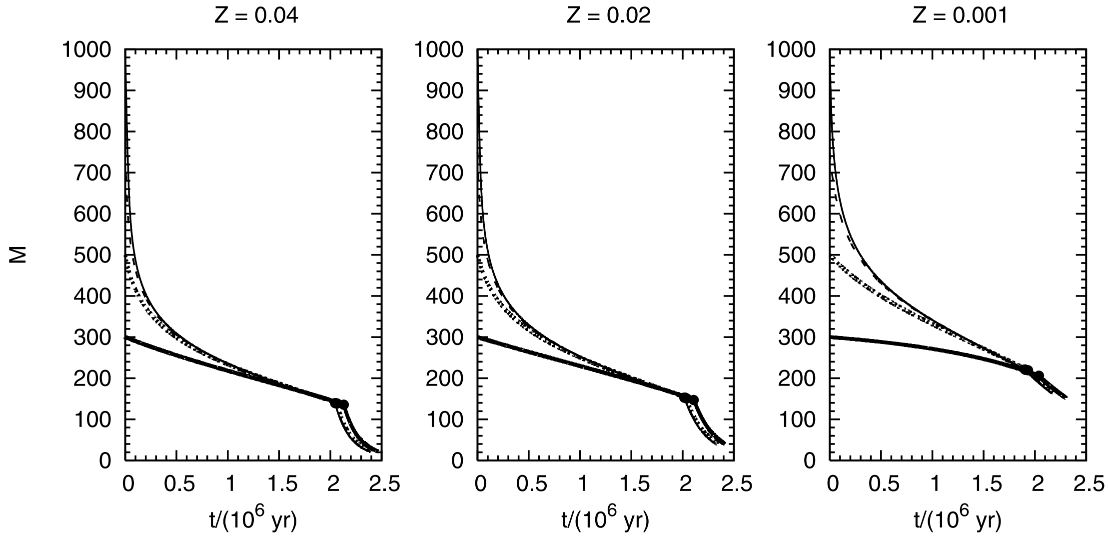


FIG. 3.—Temporal evolution of the mass (in $M_{\odot}$) for the stars with initial mass = 1000, 750, 500, and 300 $M_{\odot}$. The dots correspond to the end of CHB = the beginning of the WR phase.

than 65–75 $M_{\odot}$, we conclude from our computations and the argumentation above that it is very improbable that very massive stars in the Galactic center produce black holes with a mass larger than 65–75 $M_{\odot}$.

5. SUMMARY

In the present paper we studied the quasi-homogeneous evolution of very massive stars with mass up to 1000 $M_{\odot}$, which could be the result of core collapse of young dense clusters. When the theory of radiatively driven stellar wind mass-loss applies it follows that the evolution of very massive stars is dominated by these winds during CHB and during CHeB. At solar metallicity and larger very massive stars end their live as a black hole with a mass less then 75 $M_{\odot}$. At $Z = 0.001$, the final mass of the very massive stars studied here may be a factor 2–3 larger than those at $Z = 0.02$, e.g., in low-metallicity regions the formation of

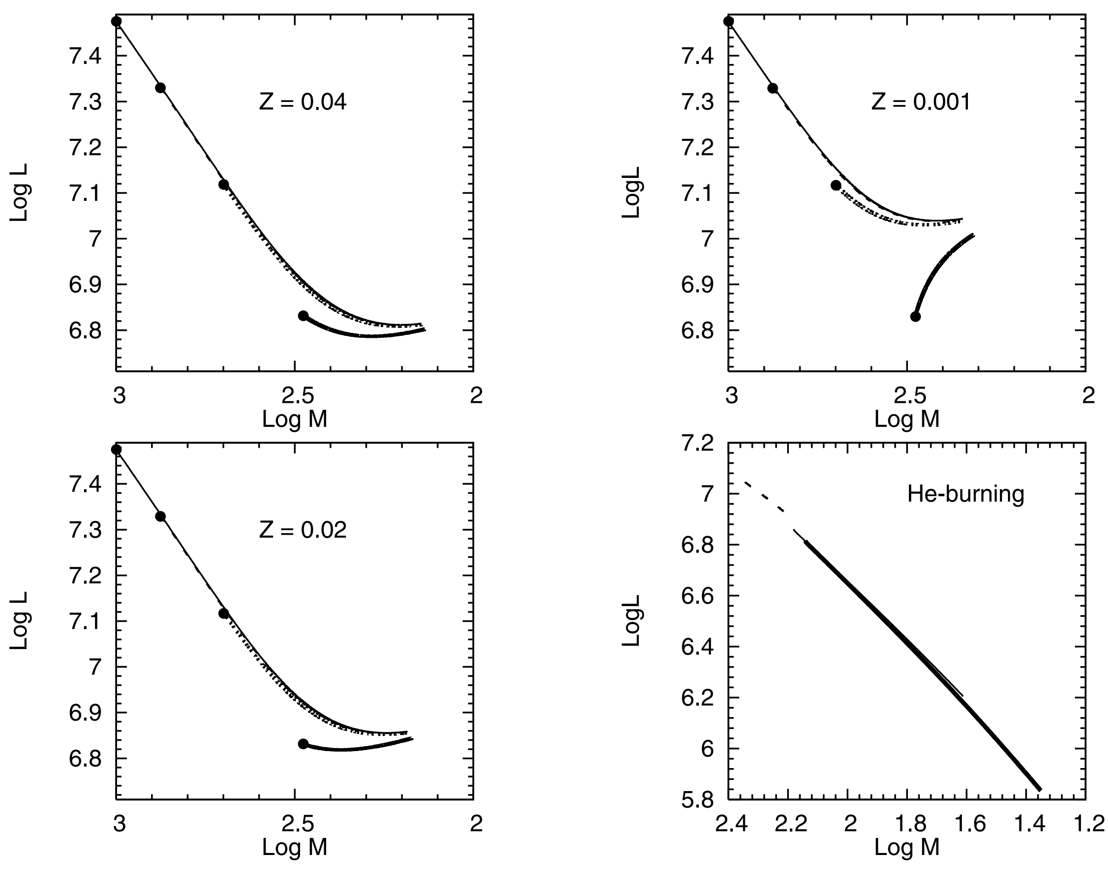


FIG. 4.—Evolution in the mass-luminosity diagram (both in solar units) of the stars with initial mass = 1000, 750, 500, and 300 $M_{\odot}$. The dots give the location of the initial zero-age parameters of the four stars. The bottom right panel shows the mass-luminosity evolution during the He-burning phase for the three metallicities: $Z = 0.001$ (*dashed line*), $Z = 0.02$ (*solid line*), and $Z = 0.04$ (*dotted line*). Notice that the three lines almost coincide.

intermediate-mass black holes with a mass of a few hundred $M_\odot$ is a possibility. Furthermore, it is very plausible that between $Z = 0.02$ and $Z = 0.001$ at least some very massive stars will end their life with a pair-instability supernova. During a pair-instability supernova very large amounts of metals may be ejected, and we suggest that the metal poor ($Z < 0.02$) chemical evolution of galactic bulges may be affected by cluster dynamics through the formation of very massive stars and the occurrence of pair-instability supernova.

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