Nucleosynthesis constraints on the First Stars

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Star formation and accretion calculations have recently suggested that the first stars are composed of Very Massive Stars (VMS). On the other hand, very massive supernovae (SN) explosion calculations have suggested that the VMS hypothesis is inconsistent with abundance determinations in Extremely Metal Poor (EMP) stars. As an alternative scenario, we propose that the first stars are born very massive but their mass reduced to the Massive Star (MS) range during their hydrogen and helium burning phases. In this paper we present some details of Zero Age Main Sequence (ZAMS) models and evolutionary calculations of a mass losing $500M_{\odot}$ Pop III star. The results indicate that VMS have very high effective temperatures, a large ratio of radiation to total pressure and a luminosity close to the Eddington luminosity and hence, we expect them to have significant radiation driven winds. For conservative evolution our evolutionary tracks are similar to those found in the literature but with the introduction of mass loss the evolution changes strongly and we have shown that VMS can reduce its mass to the MS range if the mass loss parameter N is equal or greater than ~ 300. We have estimated the total amount of matter ejected through winds until the end of the helium burning phase. The proposed scenario suggests that the first stars are born VMS but transformed into MS during their hydrogen and helium burning phases, end as black holes or hypernovae producing the Fe-rich and r-poor abundances observed in EMP stars, and that could be connected to low redshift gamma-ray bursts and the reionization of the Universe.

Keywords: Stellar evolution; first stars; population III stars; mass loss.

Cálculos recientes de formación estelar y acreción han sugerido que las primeras estrellas están compuestas de Estrellas Muy Masivas (VMS). Por otro lado, cálculos de explosiones de supernovas muy masivas (SN) han sugerido que la hipótesis VMS es inconsistente con determinaciones de abundancias en estrellas Extremadamente Pobres en Metales (EMP). Como un escenario alternativo proponemos que las primeras estrellas nacen como muy masivas, pero su masa es reducida al rango de las estrellas masivas (MS) durante sus fases de quemado de hidrógeno y helio. En este artículo presentamos algunos detalles de modelos de edad cero de la secuencia principal (ZAMS) y cálculos evolutivos de una estrella Pop III de $500M_{\odot}$ con pérdida de masa. Los resultados indican que las VMS tienen temperaturas efectivas muy altas, una alta razón de la presión de radiación a la presión total y una luminosidad cercana a la luminosidad de Eddington y por lo tanto, esperamos que estas estrellas tengan vientos significativos impulsados por radiación. Para evolución conservativa nuestras trayectorias evolutivas son similares a las encontradas en la literatura, pero cuando se introduce pérdida de masa, la evolución cambia fuertemente y hemos demostrado que las VMS pueden reducir su masa al rango de las MS si el parámetro N de pérdida de masa es igual o mayor que ~ 300. Hemos estimado la cantidad total de materia expulsada a través de vientos hasta el final de la fase de quemado de helio. El escenario propuesto sugiere que las primeras estrellas nacen como VMS pero son transformadas en MS durante las fases de quemado de hidrógeno y helio, acaban como agujeros negros o hipernovas produciendo las abundancias ricas en Fe y pobres en elementos r que son observadas en estrellas EMP, y que podrían estar relacionadas con ráfagas de rayos gamma con corrimiento al rojo bajo y la reionización del Universo.

Descriptores: Evolución estelar; primeras estrellas; estrellas de población III; pérdida de masa.

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1. Introduction

According to the Big Bang Theory, after hydrogen recombination at a redshift $z \sim 1300$, the baryonic matter in the Universe remained neutral until the first stars and galaxies started to form. However, in order to explain background radiation anisotropies it has been proposed that an intergalactic hydrogen reionization occurred between $z \sim 11$ and $z \sim 30$ [6]. Uncovering the exact time and physical conditions that gave rise to this event is one of the most important outstanding issues in cosmology, and has been the subject of much recent theoretical investigation. As a possible radiation-source that could be responsible for reionization of the interstellar medium as well as for its contamination by metals, a first generation of massive and/or very massive stars has been proposed. When these stars explode as supernovae, they eject metals as well as $\sim 10^{59}$ ergs of energy through photons into the surroundings; so that if at least 10% of the emitted photons have energy near that of the Lyman-α forest, it is enough to reionize the surroundings which have a density between 10^2 and 10^5 particles/cm^3, assuming this density as the one for the warm intercloud and ionized medium at $z \sim 11$ and $z \sim 30$. According to the point-source-model, a very massive star with a mass M, temperature T and radius R, must roughly satisfy the instability condition $(3/8)M^2GR^{-4}(1 - r/R) < (1/3)aT^4$, for $r < R$, where a is the black body radiation constant and G the gravitational constant. This expression states that when radiation dominates, massive stars are always unstable. In order to seek stability conditions for a massive star one must find the physical conditions for hydrostatic equilibrium. Besides, it is necessary to know a mass-luminosity relation and an initial mass function (IMF). The determination of both is not easy because up to now very massive stars have not been observed. Some theoretical relations have been proposed on the basis of Luminous Blue Variable (LBV) stars as very massive stars [19], however, it is not conclusive because LBV could be binary stars instead of VMS. As regards to the IMF, Tumlinson *et al.* proposed that for stars with masses between $10M_\odot$ and $50M_\odot$ the ionizing efficiency (ionizing photons per baryon) is sharper [43]. On the other hand, Oey *et al.* [32] suggest an upper mass cutoff around $120 - 200M_\odot$.

This controversial scenario shows that the study of VMS is relevant and in this context we suggest that ZAMS first stars are composed of VMS that during their hydrogen and helium burning phases lose mass polluting the intergalactic medium with hydrogen, helium, and some metals so that at the end of the quasi-static burning phases, the mass of the star has been reduced to the MS range.

In Sec. 2, we briefly summarize the relevant assumptions for the first stars IMF. In Sec. 3 we discuss some conflicting ideas about the role VMS could play in the cosmological scenario and propose an alternative one. In Sec. 4, ZAMS and stellar evolution calculations are presented, and in Sec. 5 the results are discussed.

2. Remarks on the First Stars IMF

Stars and Stellar Objects can be classified into the following mass branches: Supermassive Objects (SMO) must have masses greater than $\sim 10^5M_\odot$, the mass of Very Massive Stars (VMS) range from $\sim 10^2M_\odot$ to $\sim 10^5M_\odot$, Massive Stars (MS) are between $\sim 4M_\odot$ and $\sim 100M_\odot$, and finally normal or low mass stars have masses from a few $M_\odot$ down to $\sim 0.08M_\odot$ [12]. The debate about the existence and features of first stars VMS and MS is relevant because some cosmological puzzles can be explained, namely the reionization and the presence of small amounts of metals in the EMP stars.

It has frequently been suggested that the IMF is top-heavy at early times, *i.e.*, is biased towards massive stars with masses between $10^2M_\odot$ to $10^3M_\odot$. An IMF $\sim (M/M_\odot)^{-x}$, with $x = 1.35$, has been suggested by Salpeter [38] and accepted as universal Salpeter-like form for *a posteriori* analysis of IMFs. In this regard, Larson [24] analyzed the possibility that the IMF has a moderate variability with time and argued that for very large masses x could be equal to 2.2. With respect to theoretical estimations of the final evolution of MS and VMS stars, Nakamura *et al.* [30] have found that a star with $M \geq 250M_\odot$ could collapse completely into a black hole without ejecting any metals, whereas stars with masses in the range $100M_\odot \leq M \leq 250M_\odot$ could be partially or completely disrupted because of electron-positron pair instability; particularly, for $M \geq 150M_\odot$ the core probably disrupts completely and all of the ejected material containing metals, could pollute the interstellar medium (IM). These authors found that stars with $35M_\odot \leq M \leq 100M_\odot$ could evolve into a black hole and for $10M_\odot \leq M \leq 35M_\odot$ explode as Type II supernova.

In order to make an estimate on the mass of Population III stars, the chemical composition plays a relevant role. Assuming a primordial gas composed of $H, H^+, H^-, e^-, He, He^+, He^{++}, H_2$, and H_2^+, Abel *et al.* [3] found, by three-dimensional numerical simulations, that the first formed stars have an uncertain final mass but a single molecular protostar of $\sim 1M_\odot$ at the center of a $\sim 100M_\odot$ core is formed. In previous papers, Abel and collaborators [1–3] found cores of the order of $50M_\odot$ to $\sim 200M_\odot$. In Abel's numerical simulations the cores are important because it is expected that the cores fragment into stars or star clusters, in such a case these stars should have masses less or equal to the core masses which can be associated to the VMS or MS. With different physical constraints, Nakamura *et al.* [29] have performed one-dimensional hydrodynamical simulations and found $3M_\odot$ as the mass of the first star but due to accretion such star could grow up to $\sim 16M_\odot$. As a result of a two-dimensional hydrodynamical simulations, it is predicted that the IMF of Population III stars could be bimodal with peaks of $\sim 1 - 2M_\odot$ and $\sim 10^2M_\odot$ [30]. Bromm and collaborators [9] pointed out that the Population III stars might have masses up to $\sim 10^4M_\odot$. There is also a one-zone model of chemical evolution [7] which leads to the conclusion that these stars can have $M \lesssim 0.8M_\odot$. Omukai *et al.* [33] followed the evolution of accretion protostars and found $\sim 600M_\odot$ as the upper limit for massive stars, although it is relevant to notice that star formation is sensitive to the mass accretion rate and its time variations. In a recent paper, Tumlinson et al. [43] pointed out that the sole generation of VMS ($M > 140M_\odot$) can not be possible, and they suggest that some VMS could be formed as companions of stars with masses $M < 140M_\odot$. Tumlinson *et al.* IMF proposition match quite well with the reionization and nucleosynthesis evidence. Tegmark *et al.* [41] argue that the minimum baryonic mass is redshift dependent and is lying in the range from $\sim 10^{3.7}M_\odot$ to $10^6M_\odot$, for $z \sim 10$ and $z \sim 15$, respectively, and they pointed out that a participation of 10^{-3} of the whole baryonic matter in the generation of luminous stars is sufficient to reheating the Universe at $z \sim 30$.

The proposed first stars are assumed to be responsible for the initial enrichment of the intergalactic medium (IGM) with heavy elements [10]. Numerical simulations suggest that first stars were VMS, with masses $> 100 M_\odot$ [2, 3, 9, 10, 30]. Bromm and Larson have reviewed recent theoretical results on the formation of the first stars [11]. The exact determination of the stellar masses, and the precise form of the primordial initial mass function, is still under discussion.

3. An alternative Scenario

About two decades ago, the existence of VMS, whose mass lies between 10^2 and $10^5 M_\odot$, as well as of Super Massive Objects, with masses greater than $10^5 M_\odot$, was questioned mainly under the belief that such stars could be unstable. In fact, it was alleged that stars with masses greater or equal than $\sim 60 M_\odot$ were vibrationally unstable to nuclear energizing pulsations that could induce eruptions and/or very strong winds [26, 51]. However, it has recently been claimed that stars with masses less or equal than $\sim 500 M_\odot$ are far less vibrationally unstable than previously thought, and may reach the end of their evolution with a massive helium core [17]. In addition, studies on the stability of metal-free and metal-enriched massive stars show that metal-free stars with masses in the range $120 M_\odot < M < 140 M_\odot$ become stable after about one third of their hydrogen burning lifetime [5]. Nevertheless, it must be pointed out that the mentioned calculations may have a limited significance because they are based on the "flux-freezing convection theory". This theory assumes that the perturbation in the luminosity is given solely by the perturbation in the radiative luminosity. However, the stability properties of the models could change strongly if convection is properly taken into account. Besides, other effects that are normally neglected, such as rotation and magnetic fields, present in VMS stars, could also affect the stability. Thus, the issue of whether VMS could be vibrationally unstable to pulsations and induce pulsationally driven winds is still open. A number of estimates and propositions of the typical mass of the pristine stars have been put forward. For example, it has been suggested that the IMF of pregalactic stars may be in the VMS range [24]. However, the IMF of stars is a very difficult parameter to be observationally determined because one observe stars at very widely differing stages of evolution and corrections for the lifetimes of different masses must be done . An empirical determination of the upper mass limit for the stellar IMF depends on the assumption of whether the highest mass stars have already expired or they can still be observed. The ideas sketched in this paper imply the actual possibility of the existence of VMS as pristine stars.

Recently, it has been distinguished between what has been called the strong and the weak VMS hypothesis. In the former, the first generation of stars was completely composed of VMS, whereas in the latter the first generation included VMS in addition to stars with masses less or equal to $\sim 40 M_\odot$ [43]. The weak VMS hypothesis is in fact an almost normal star formation with the addition of some VMS. However, the VMS hypothesis and the hypernovae scenario [43] are not necessarily inconsistent if VMS have considerable mass loss during their quasi-static evolutionary phases. In recent papers, it has always been assumed that VMS evolve with no mass loss, so that they reach the SN stage with almost their initial main sequence mass [43]. However, the SN mass could be much smaller than the zero-age main sequence mass [4], and in order to keep the VMS hypothesis, we suggest a new scenario with the following two cornerstones: VMS are formed but their masses are reduced to the MS range by winds during the hydrogen and helium burning phases [4], and that a fraction of $\sim 10^{-3}$ of the baryons in the Universe are incorporated into VMS [41]. The consequences of these assumptions are the following: through winds, VMS produce at least part of the CNO elements observed in EMP stars [4], the VMS evolve to MS during the hydrogen and helium burning phase and end as hypernovae producing the Fe-rich and r-poor abundances observed in EMP stars [31, 44, 45] that could be connected to low redshift gamma-ray bursts [31,44,45] and the reionization of the Universe [4, 41, 43].

4. Evolution and Nucleosynthesis of Very Massive Stars

In this section we first describe some details of the structure of ZAMS stars with masses from 100 to $10,000 M_\odot$. We then present evolutionary calculations for a $500 M_\odot$ Pop III star. A more complete set of models will be presented in Bahena et al. [4]. The models are assumed to have the following initial compositions: For Pop I $(X, Z) = (0.74, 10^{-2})$, for Pop II $(X, Z) = (0.749, 10^{-4})$, and for Pop III $(X, Z) = (0.765, 10^{-6})$. We also define the Population IV (Pop IV) composition $(X, Z) = (0.765, 10^{-9})$, and the Pregalactic population (Pop P) with $(X, Z) = (1.0, 10^{-10})$. For the mass loss rate we take the empirical relation $\dot{M} = NL/c^2$, where N is a constant, L the luminosity, c the speed of light and the dot denotes a derivative with respect to time [21]. For MS, N is in the range 100-300, for VMS we expect N to have higher values, perhaps up to 500 or 1000 [4].

As will be described in Bahena *et al.* [4], the characteristics of the ZAMS models depend upon the mass of the star and its metallicity. The effective temperature increases with mass and depends strongly upon the metallicity. For the VMS range, the effective temperature is of about $60,000 K$, $67,000 K$, $84,000 K$, $108,000 K$ and $112,000 K$ for the compositions Pop I, Pop II, Pop III, Pop IV and Pop P, respectively [4]. Hence, for low metallicity, VMS have very high effective temperatures which are translated into high ratios of radiation to total gas pressure, but the ratio of the luminosity to the Eddington luminosity diminishes with decreasing metallicity, since the opacity gets smaller. The ratio of the luminosity to the Eddington luminosity is given by the expression $L/L_{Edd} = \kappa_\nu L/4\pi cGM$, where κ_ν is the real mass absorption coefficient and the other symbols have their usual meaning. Therefore, our L_{Edd} corresponds to the modified Eddington luminosity. The VMS high values of L/L_{Edd} coupled to their well known instability to nuclear energizing pulsations [26, 51] suggest that they have strong winds.

The convective core size is defined as $q_{cc} = M_{cc}/M_*$, where M_{cc} is the mass of the central convective region and M_* the total mass of the star. Very Massive Stars have a large central convective region and the models become almost fully convective for high enough masses, with a weak dependence upon metallicity [4].

As an example of the evolution of a mass losing VMS, we present in Fig. 1 the evolution until the end of the helium burning phase of a $500M_\odot$ Pop III star with a mass loss parameter N = 0, 100, 200, 300 and 500. The constant mass evolution ($N = 0$) is similar to that reported by Baraffe *et al.* [5]. However, with the introduction of mass loss, the evolutionary tracks changes strongly. For the $N = 100$ case, the star evolves with an almost constant luminosity during both the hydrogen and helium burning phases as occurs for lower mass VMS. The final mass at the end of the helium burning phase is $268M_\odot$, which is still in the VMS range. For values of N higher than ~ 200, the initial evolution is characterized by a fast decrease in luminosity followed by a slow reduction in luminosity until the end of the hydrogen burning phase. For the conservative case, the effective temperature is reduced from the initial value of $85,500K$ to $51,000K$ by the end of the hydrogen burning phase. At this point in the evolution, the effective temperature is much lower for the mass losing cases, about $18,000K$. The evolution during the helium burning phase is characterized by an almost constant luminosity and a further strong reduction of the effective temperature until a rather cool temperature of about $5,000K$. For the $N = 200$ and $N = 300$ cases, the masses at the end of the calculation are $131M_\odot$ and $104M_\odot$, respectively, which are still in the VMS range. For the $N = 500$ case the final mass is $60M_\odot$ which is in the boundary between MS and VMS. When helium is exhausted in the central convective region, the central and surface density and temperature start to increase and the star collapses strongly towards very fast burnings and a supernovae explosion. The calculation in all cases was stopped shortly after the beginning of the final collapse.

A quantity that measure the importance of radiation pressure in the outer layers of the star is the ratio L/L_{Edd} of the luminosity to the Eddington luminosity. For high values of L/L_{Edd} we expect the star to suffer from strong radiation driven winds. In Fig. 2 we show ratio L/L_{Edd} as a function of the evolution time. At the start of the calculation $L/L_{Edd} = 0.796$. For the $N = 100$ case, L/L_{Edd} increases to 0.895 by the end of the hydrogen burning phase, then continues to increase during the helium burning phase until a maximum value of 0.910 that is reached when the central helium abundance has been reduced to about 0.30. Then L/L_{Edd} decreases and goes through an oscillation but maintains a rather high value until the end of the helium burning phase. The evolution for the $N = 200$ and $N = 300$ cases is very similar, the maximum values of L/L_{Edd} are 0.901 and 0.891, respectively, somewhat lower values than for the $N = 100$ case but still quite high. The evolution of L/L_{Edd} for the $N = 500$ case is also similar, but due to the strong reduction of the mass of the star, L/L_{Edd} decreases, but eventually increases during the helium burning phase and goes through an oscillation as in the lower N cases. For this case the first maximum in L/L_{Edd} is 0.868 and occurs near the end of the helium burning phase.

In Fig. 3 we show the evolution of the ratio q_{cc} of the central convective region to the total mass of the star as a function of the evolution time for all the mass losing calculations. For the initial phases of the evolution q_{cc} maintains an almost constant value but then decreases. The reduction of

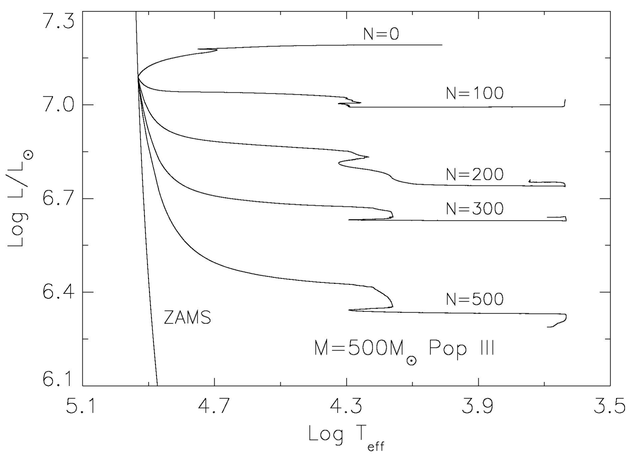

FIGURE 1. Evolution of a mass losing $500M_\odot$ Pop III star. $L/L_\odot$ is the luminosity in units of the solar luminosity, T_{eff} is the effective temperature and the mass loss parameter is N. We also show ZAMS models for the same composition.

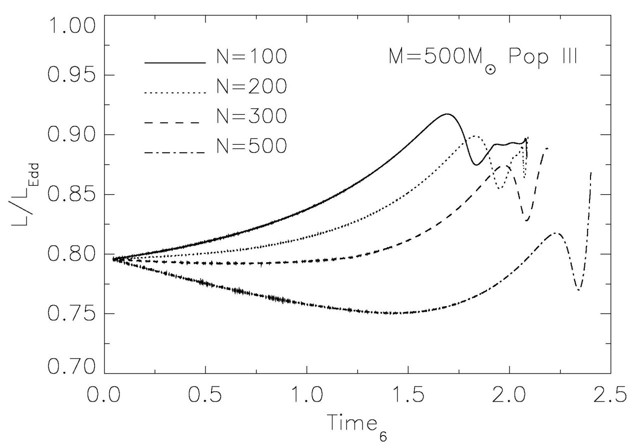

FIGURE 2. Ratio of the luminosity L to the modified Eddington Luminosity L_{Edd} during the hydrogen and helium burning phase as a function of the evolution time in units of millions of years for the mass losing models. The mass loss parameter is N.

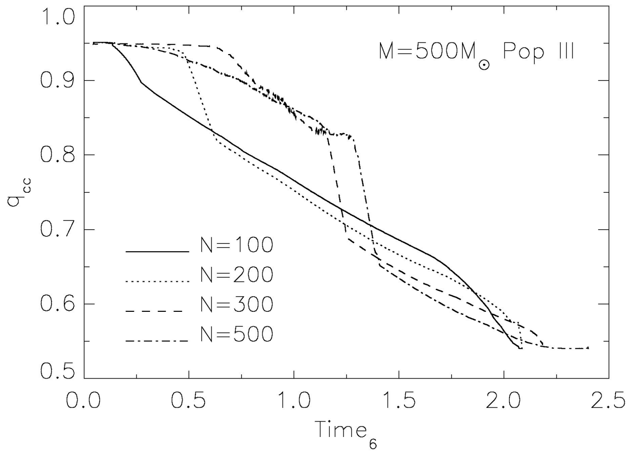

FIGURE 3. Convective core size q_{cc} during the hydrogen and helium burning phase as a function of the evolution time in units of millions of years for the mass losing models. The mass loss parameter is N.

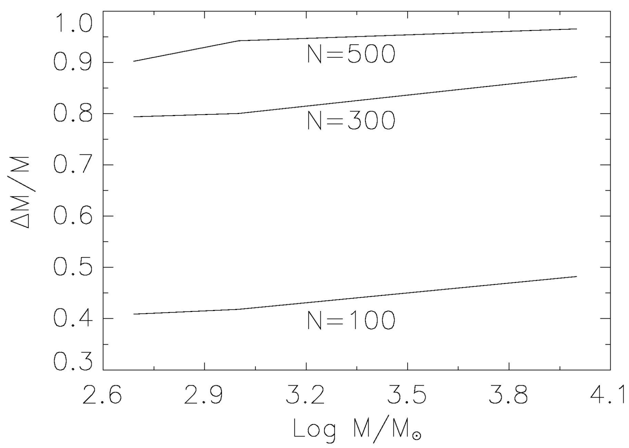

FIGURE 4. Fraction of the total mass lost during the evolution as a function of the initial mass of the star.

q_{cc} occurs later in the evolution for higher values of N but by the end of the hydrogen burning phase and through the helium burning phase, q_{cc} follows a similar trend for all mass losing calculations. Hence, the models stay almost fully convective for a longer time for the higher N cases. This is because with high mass loss rates the star remains almost chemically uniform but eventually a composition gradient develops and the value of q_{cc} is reduced. In Bahena *et al.* [4] an analytic model for the evolution of q_{cc} with respect to the central hydrogen abundance will be presented.

A summary of the total mass lost through winds as a function of the initial mass of the star $(\Delta M/M)$ is presented in Fig. 4. For all values of the mass loss parameter N, the total mass lost depends weakly on the mass of the star although slowly increasing with higher masses. The percentage of hydrogen ejected is approximately 18%, 40% and 53% for the $N = 100$, 300 and 500 cases, respectively. The corresponding figures for helium are 24%, 39% and 41%, respectively. The percentage of mass lost through winds in the form of C^{12} and O^{16} is about 1.5% in each of these species for almost all masses and mass loss rates. The percentage of mass lost in the form of N^{14} is quite small, less than about $\sim 0.01\%$ for masses up to $\sim 1,000 M_\odot$ and about $\sim 0.05\%$ for stars in the $\sim 10,000 M_\odot$ region. Hence, the total amount of metals returned to the interstellar medium by most masses and mass loss rates is about $2 - 3.5\%$ for the quasi-static evolutionary phases. Summing up all the contributions, the total amount of matter ejected for stars below $\sim 1,000 M_\odot$ is about 41, 67, 80 and 92% for the $N = 0$, 200, 300 and 500 cases, respectively. The corresponding figures for stars in the $\sim 10,000 M_\odot$ region are 49, 88 and 96% for the $N = 0$, 300 and 500 cases, respectively.

A standard practice in most stellar evolution calculations is to assume a similar mass loss rate for all the calculation. This may be approximately correct for stars that loses only a small fraction of their initial mass, but for cases where a significant reduction of the star's initial mass occurs, the mass loss formulation should be modified. The calculations presented in this paper have been performed with a constant value of N. It may be more realistic to consider evolutions with variable N which becomes smaller as the mass of the star is reduced from the VMS to the MS range. This possibility will be discussed in a future communication.

5. Discussion

Recent star formation calculations suggest the existence of a pregalactic generation of VMS [2, 10, 25], that are assumed to evolve with no mass loss until they encounter the pair-creation instability [17]. On the other hand, several authors have suggested (see, for example Tumlinson *et al.* [43] and cited references) that the yields of VMS supernovae are inconsistent with abundance determinations of EMP stars. In order to resolve this controversy we propose a new scenario in which the first stars are born very massive but transformed into massive stars through winds during their quasi-static burning phases.

In this paper we have discussed some of the characteristics of ZAMS models from 100 to $10,000 M_\odot$, and presented the evolution of a $500 M_\odot$ Pop III star with a mass loss parameter $N = 0$, 100, 200, 300 and 500. The results indicate that VMS have very high effective temperatures, a large ratio of radiation to total pressure and a luminosity close to the Eddington luminosity. The evolution is started with a value of $L/L_{Edd} = 0.796$ that increases to a maximum value of 0.910, 0.901, 0.891 and 0.868 for the $N = 100$, 200, 300 and 500 cases, respectively. The high L/L_{Edd} values suggest that VMS have significant radiation driven winds. In addition, VMS suffer from the well known instability to nuclear energizing pulsations [26, 51]. Recently, Heger *et al.* [17, 18] found that stars with masses less or equal than $500 M_\odot$ are far less vibrationally unstable than previously thought, and may reach the end of their evolution with a massive helium core that encounter the pair-creation instability [5, 17]. We have argued that the recent calculations [5, 17] have limited significance because of the use of the so called "flux-freezing convection theory". The stability properties of the models could change strongly if convection and other effects are properly taken into account. Thus, VMS are expected to have high mass loss rates as a result of the combination of high L/L_{Edd} values and nuclear energizing pulsations.

For conservative evolution $(N = 0)$ our evolutionary tracks are similar to those of Baraffe *et al.* [5]. However, with the introduction of mass loss the evolution changes strongly and we have shown that VMS can reduce its mass from the VMS to the MS range if the mass loss parameter N is equal or greater than ~ 300.

The total amount of matter ejected through winds until the end of the helium burning phase is about $41 - 49\%$, $67 - 75\%$, $80 - 88\%$ and $92 - 96\%$ for the $N = 0$, 200, 300 and 500 cases, respectively, where the lower limit corresponds to stars around $250M_{\odot}$ and the upper limit to stars around $10,000M_{\odot}$. The total amount of metals returned to the interstellar medium by most masses and mass loss rates is about $2 - 3.5\%$ for the quasi-static evolutionary phases.

Chemical elements heavier than lithium are thought to be produced exclusively through stellar nucleosynthesis. The primordial cosmic gas remains pristine until the first supernovae explosions expel metals that are produced in the precursor stars. It is often suggested that the origin of these heavy elements may be attributed to the first generation of stars, the Population III stars [28,34–37,42].

In the standard cosmological models based on cold dark matter, the first cosmological stars are predicted to form at redshift greater than ~ 20 [1, 14, 41, 49]. Thus, the first heavy elements are likely to have been processed at such early epochs.

Measurements by the *Wilkinson Microwave Anisotropy Probe (WMAP)* satellite [22, 40] provides evidence that the universe was reionized very early on, and the first stars could form at a redshift greater or equal than about 20 [13,16,39,47,48].

If the first stars are indeed as massive as $\sim 200M_{\odot}$, they end their lives as energetic SN via the pair-instability mechanism [7,8,15], releasing a total energy of up to $\sim 10^{53}$ ergs. Since massive stars process a substantial fraction of the mass into heavy elements, early SN explosions may provide an efficient mechanism to enrich the intergalactic medium [49,50].

Heger and Woosley [18] in their stellar evolution models predict that in massive zero-metallicity stars, up to $\sim 40 - 50\%$ of the total stellar mass is processed into heavy elements in the core, and in the pair-instability case all of it is finally ejected during the explosion. Because of the short lifetimes of such massive stars, prompt metal enrichment could be achieved efficiently by Population III SN in the early universe. They explore the nucleosynthesis of helium cores in the mass range $M_{\rm He} = 64 - 133M_{\odot}$, corresponding to main-sequence stellar masses of $\sim 140 - 260M_{\odot}$. Above $M_{\rm He} = 133M_{\odot}$, a black hole is formed and no material is ejected. For lighter helium core masses, $\sim 40 - 63M_{\odot}$, violent pulsations occur, induced by the pair instability and accompanied by supernova-like mass ejection, but the star eventually produce a large iron core in hydrostatic equilibrium. In the models of Heger and Woosley [18] the precollapse winds and pulsations of the stars results in small amounts of mass loss [5,23,46].

We have then proposed an scenario where the first stars are born VMS but transformed into MS during their hydrogen and helium burning phases and end as black holes or hypernovae producing the Fe-rich and r-poor abundances observed in EMP stars [31, 44, 45] that could be connected to low redshift gamma-ray bursts [31, 44, 45] and the reionization of the Universe [4,41,43].

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