REVISTA MEXICANA DE FÍSICA S **54** (3) 74–80 DICIEMBRE 2008

The final fate of very massive first stars

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Recibido el 1 de marzo de 2008; aceptado el 25 de junio de 2008

A generation of stars which formed from primordial nearly pure H/He gas, the so-called *first stars* or Population III stars, must have existed since heavy elements can only be synthesized in the interior of the stars. These stars were responsible for the initial heavy elements enrichment of the intergalactic medium. In this work we analyze the possible outcome of the evolution of very massive Population III stars and whether their final fate can avoid the pair instability supernovae explosion. We have recently calculated the evolution and nucleosynthesis of mass losing very massive population III stars during the hydrogen and helium burning phases, and proposed a new scenario for the *first stars* in the universe. According to this scenario, the *first stars* were born very massive, but evolve with mass loss, and its possible endpoint is a hypernovae stage. At low metallicity the effects on the presupernova structure depends on the initial mass and the mass loss rate during the main sequence evolution. Presupernova stars of lower metallicity have different characteristics depending if they are galactic or pregalactic, and if they evolve without or with mass loss. When these stars evolve with mass loss, their convective core size increase and their helium- or carbon-oxygen core mass decreases. Then, the stars could explode like hypernovae or supernovae.

Keywords: First stars – stars: Population III; stellar evolution; mass loss; final fate.

Una primera generación de estrellas formada de gas primordial casi puro de H y He, las llamadas *primeras estrellas* o estrellas de Población III, debió haber existido ya que los elementos pesados solo pueden ser sintetizados en el interior de las estrellas. Estas estrellas fueron responsables del enriquecimiento inicial del medio intergalactico en elementos pesados. En este trabajo, analizamos el posible desenlace de la evolución de estrellas muy masivas de la Población III y cuando, su destino final, puede evitar la explosión de supernova por inestabilidad de pares. Recientemente hemos calculado la evolución y nucleosíntesis de estrellas muy masivas de población III con pérdida de masa durante los quemados de hidrógeno y helio, y propuesto un nuevo escenario para las primeras estrellas del universo. De acuerdo a este escenario, las primeras estrellas nacieron muy masivas pero evolucionaron con pérdida de masa terminando su vida como hipernovas. A baja metalicidad los efectos de la estructura presupernova depende de la masa inicial y de la tasa de pérdida de masa durante la secuencia principal. Las estrellas de presupernova de baja metalicidad tienen diferentes características dependiendo de si son galácticas o pregalácticas y si evolucionan con o sin pérdida de masa. Cuando evolucionan con pérdida de masa, el tamaño de su núcleo convectivo aumenta y las masas de sus núcleos de helio o de carbono-oxígeno disminuyen. Por consiguiente, estas estrellas podrían explotar como supernovas o hipernovas.

Descriptores: Primeras estrellas – estrellas: Población III, evolución estelar; pérdida de masa; destino final.

PACS: 97.10.Cv; 97.10.Me; 97.10.Zr; 97.20.Wt

1. Introduction

The mass range of very massive stars (VMS) extends from $\sim 10^2$ to $\sim 10^5 M_\odot$. Population III stars mean those of nearly zero metallicity and generates the first metals because they can only be produced through stellar nucleosynthesis. This scenario and the constrains which come from the background light and nucleosynthetic considerations was reviewed by Carr [1], that suggested that the *first stars* were more massive than those forming today. It is also possible that most of the baryons were processed through a first generation of pregalactic stars and that Population III stars provided at least some of the dark matter in galactic halos in the form of black holes. Primordial stars are expected to produce radiation, explosions and nucleosynthesis products, and each of these could have important cosmological consequences.

Stars with an initial mass above $100M_\odot$ are radiation-dominated and therefore unstable to pulsations during hydrogen burning. These pulsations would lead to considerable mass loss, and overproduction of helium, but are unlikely to disrupt the star completely. First clouds could also collapse directly to black holes [2]. Stars larger than some critical mass ($\approx 200M_\odot$) undergo complete collapse, and they are better candidates to produce dark matter than ordinary stars. Numerical studies indicate a great consensus that sufficiently large very massive stars collapse to black holes, while smaller ones explode. Klapp concluded that VMSs are the most suitable candidates for Population III objects [3,4], Klapp:1984. VMSs has also been considered to dominate in causing various feedback effects on the intergalactic medium (IGM) in the early universe such as ionization, heating, and chemical enrichment [5].

Heger *et al.* investigated the occurrence of the pair instability following the evolution of chemically homogeneous helium cores of "zero" metallicity stars, assuming no mass loss by winds [6]. During the contraction phase towards central oxygen burning of helium cores of $\sim 42 M_\odot$ or more [7-9],the temperature in the center gets as hot as $T_{\rm c} \gtrsim 3 \times 10^9$ K, while the density remains low; it is during this phase that the electron-positron pair instability is encountered. Pairs are created from the radiation field, contraction is not stopped prior to the onset of central oxygen burning and this leads to explosive oxygen or even silicon burning.

For larger helium core masses, the stars are totally disrupted after a few pulses, *i.e.*, the last pulse is violent enough to completely disrupt the star without leaving a compact remnant. For larger masses, the star explodes in only one pulse. For core masses $\gtrsim 140 M_\odot$ the star collapses into a black hole. A $150 M_\odot$ star develops a $\sim 71 M_\odot$ helium core and it is disrupted at its third pulse [6].

The supernova explosions that ended the lives of the *first stars* were responsible for the initial enrichment of the intergalactic medium with heavy elements [5]. An interesting possibility unique to zero-metallicity massive stars is the complete disruption of their progenitors in pair-instability supernovae explosions, which are predicted to leave no remnant behind [10-13]. The last ones consider that this peculiar explosion mode could have played an important role in quickly seeding the intergalactic medium with the first metals.

This work is organized as follows: In §2 we describe an alternative scenario for the *first stars* evolution. In §3 we discuss the possible endpoint of these stars. Then, in §4 we describe some results for the studied stars. In §5 and §6 we discuss our results in comparison with others authors. Finally, in §7 we outline our conclusions.

2. The first generation of stars

A review of recent theoretical results on the formation of the *first stars* in the universe has been made by [14]. They constitute the so-called Population III stars [1,3,4]. The first generation of stars had important effects on subsequent galaxy formation, they produce important amounts of UV photons to reionize the universe [15].

Many recent papers have investigated VMS evolution, including stability calculations assuming constant mass. In this work we suggest that very massive stars are formed but their mass reduced to the massive star range by mass loss before the end of the helium burning phase. We have studied the structure, evolution and nucleosynthesis of mass losing very massive stars ($M \geq 100 M_\odot$) for metal-free and nearly metal-free Population III stars. Metal-free stars are hotter and smaller than their metal-enriched counterparts. These features have interesting implications for the formation, environment, and particularly the spectra of the *first stars*, and important cosmological consequences as well.

Our proposal of a VMSs scenario includes the following:

i) Very massive *first stars* are formed but their mass reduced to the massive star range during the hydrogen and helium burning phases.

ii) If a fraction of $\sim 10^{-3}$ of the baryons in the universe is incorporated into very massive *first stars* [16], the consequences are:

  a) Very massive *first stars* contributed to the early enrichment of the intergalactic medium with heavy elements, and produce at least part of the Carbon and Oxygen observed in Extremely Metal-Poor (EMP) stars;
  b) Very massive *first stars* evolved to massive stars during the H- and He-burning phases and ended their lives as hypernovae producing the Fe-rich and *r*-poor elements observed in EMP stars [17-21];
  c) The suggested hypernovae could be connected to low-z gamma-ray bursts [17,20,21];
  d) Depending upon the mass loss rate, VMS could avoid the pair instability supernovae explosion;
  e) Very massive *first stars* reionized the universe as well [5,16,22].

3. The endpoint of VMS evolution

3.1. Pair-instability supernovae

A review of the physical processes held responsible for Type I and II supernovae explosions (SNe), and the observable diagnosis of the models was done by [8,9]. Concerning massive stars explosions ($M \gtrsim 60 M_\odot$), after helium exhaustion, the central region of the star contracts, and since helium burning produces small amounts of carbon and neon ($\sim 5\%$ each by mass), the star goes directly to oxygen ignition. However, if the helium core mass exceeds about $32 M_\odot$ (main sequence mass $\gtrsim 65 M_\odot$), oxygen burning is not cuasi-static, the star keeps collapsing and the "pair-instability" occurs because at temperatures around 2×10^9 K, a large portion of the gravitational energy released goes into the creation of the rest mass of electrons and positrons [23]. A violent pulsation instability occur in stars with main-sequence masses between about 65 and $120 M_\odot$. Complete explosion occurs from 120 up to about 300 $M_\odot$. Beyond this point a black hole is formed.

Massive star ($> 45 M_\odot$) pulsating explosions are especially interesting. During these events, several solar masses of helium and helium-burning products are ejected [8]. The pair instability core explosion produces a supernova that is classified as Type II. The critical mass for which nuclear burning is able to overcome the electron-positron pair instability and cause an explosion in a non-rotating star is $200 - 300$ M$_\odot$ [7,24]. Without rotation or catastrophic mass loss of a large fraction of the star's mass just prior to the collapse, a more massive star becomes a black hole.

If an early partial reionization of the universe is produced by Population III stars, as may be required by the WMAP results, this will have resulted in a nearly uniform enrichment of the universe to a level $Z_{\min} \geq 10^{-4} Z_\odot$ already at $z \gtrsim 15$ [25]. For the most energetic pair-instability supernovae (PISNe) explosions, these metals are in the form or iron, and the systems could have been responsible for an early burst of Fe enrichment [10]. The “prompt inventory” [26] could have arisen in the PISNe.

Theoretical analysis predict the final fate of massive metal-free stars [6,27]. Fryer, Woosley and Heger considered the evolution of two zero-metallicity stars of 250 and $300 M_\odot$ neglecting mass loss [11]. These stars produced helium cores of 130 and $180 M_\odot$. In the first case, explosive oxygen and silicon burning cause the helium core to explode but, in the second one, an explosive burning is unable to drive the explosion and it collapses to a black hole.

The ultimate fate of a metal-free star depends critically on its mass. Recent theoretical models suggest the following scenarios [12,13]:

1. Stars with mass $25 < M < 250 M_\odot$ that explode as core-collapse supernovae explosions and leave a neutron star behind.

2. Stars with mass $25 < M < 40 M_\odot$ that explode as faint Type II SNe and leave black holes behind after fall-back of most of the envelope [20, 21].

3. Stars with mass $40 < M < 140 M_\odot$ that do not explode as SNe and directly collapse into black holes.

4. Stars with mass $100 < M < 140 M_\odot$ that experience a pulsational instability and eject their outer envelope, again leaving a black hole behind.

5. Stars with mass $140 < M < 260 M_\odot$ that explode as pair-instability SNe, causing complete disruption.

6. Stars with mass $M > 260 M_\odot$ that in the absence of rotation collapse directly into massive black holes.

However, the observed abundances of metal-poor stars are better explained by hypernovae (HNe) explosions and not by $M \simeq 130 - 300 M_\odot$ PISNe [20]. The ejecta of core collapse supernovae explosions of $20 - 130 M_\odot$ stars can well account for the abundance pattern of EMP stars [18].

3.2. The hypernovae hypothesis

An alternative explanation to EMP abundances has been developed by [17–21]. They calculated abundance yields for explosive nucleosynthesis in core-collapse hypernovae and showed that the abundance pattern and the large ratio between the energy and the heavy-elements mass can be explained by hypernovae nucleosynthesis. Such hypernovae explosions are expected to occur for stars more massive than $M \gtrsim 20 - 25 M_\odot$. Also, they have investigated pair-instability supernovae ($\sim 150 - 300 M_\odot$) and concluded that the energy-to-heavy-element mass ratio in these supernovae is too small to explain the observations.

Recent studies of core-collapse supernovae have discovered two distinct types of supernovae explosions: (i) very energetic SNe (hypernovae), whose kinetic energy exceeds 10^{52} erg, about 10 times normal core-collapse SNe ($E_{51} = 10 - 100$, $E_{51} = E/10^{51}$ erg), and (ii) very faint and low energy SNe (faint supernovae, $E_{51} \lesssim 0.51$). These two types of supernovae are likely to be “black hole-forming” supernovae with rotating or non-rotating black holes [19].

Energetic supernovae or “hypernovae” (HNe) explosions connected to some low-z gamma-ray bursts could be relevant to early nucleosynthesis at low metallicity [20]. Recently, some massive supernovae have been found to explode much more energetically than normal Type II SNe as “hypernovae” [28, 29]. Such “hypernovae” explosions are expected to occur for stars more massive than $\sim 20 - 25 M_\odot$ [30]. However, the upper mass limit of core-collapse SNe is still uncertain.

Using Population III pre-supernova progenitor models, [17] simulated the supernova explosion and calculated detailed nucleosynthesis. In [18] it was proposed that the first generation supernovae were the explosions of $\sim 20 - 30 M_\odot$ stars and some of them produced C-rich, Fe-poor ejecta that can well account for the abundance pattern of EMP stars. In contrast, the observed abundance patterns cannot be explained by the explosions of more massive, $130 - 300 M_\odot$ stars. These stars undergo pair-instability supernovae and are disrupted completely [12, 20]. Therefore, the supernova progenitors that are responsible for the formation of EMP stars are most likely in the $\sim 20 - 30 M_\odot$ range, but not more massive than $130 M_\odot$.

4. Stellar evolution and mass loss

4.1. Initial conditions

For this work we calculated models of galactic and pregalactic Population III stars, for a wide mass range, and for three different chemical compositions which are the following: for galactic stars ($X, Z = 0.765, 1.0\text{E} - 6$), and for pregalactic stars ($X, Z = 0.765, 1.0\text{E} - 9$), and ($X, Z = 0.765, 1.0\text{E} - 10$).

4.2. Code and input physics

The system of stellar structure and evolution equations used in the numerical code has been presented in [3, 4, 31, 32]. In these papers the input physics has also been described, including the stellar equation of state, the opacity, the nuclear reactions and their rates. The mass loss rate is given by the expression $\dot{M} = NL/c^2$, where L is the luminosity of the star, c is the speed of light and N is the mass loss parameter which can take a value in the range $N = 0 - 500$. The computer code is based on Eggletons computer code, however, most subroutines have been rewritten or completely replaced by new ones. An important feature of the code is that it uses a semiconvective transport treatment through the use of a composition diffusion equation.

4.3. Evolutionary calculations

We have calculated an extensive set of stellar evolution models of 100, 150, 200, 250, and $300M_{\odot}$ massive and very massive stars, without and with mass loss, for the H- and He-burning phases. As an example, we present here the evolution of galactic and pregalactic Population III $200M_{\odot}$ stars with mass loss parameters $N = 0, 50, 100, 200$ and 300.

Figure 1 shows evolutionary tracks in the HR-diagram for $200M_{\odot}$ pregalactic Population III stars, with several mass loss parameters. The evolution was followed from the ZAMS up to just before C-ignition.

4.4. Cuasi-static evolution

The hydrogen burning phase in massive stars is characterized by a continuous movement to the right of the HR-diagram. However, investigating the evolution of very massive pregalactic stars, Klapp found that as the mass of the star is increased, the tendency to move to the right of the diagram decreases and for large enough masses, the tracks move to the left of the diagram and in some cases loops are observed [3]. This is an unique characteristic of VMSs. The actual mass at which the transition between right and left moving tracks occur depends upon the mass loss rate. In his calculations, very massive evolutionary tracks move to the right of the HR-diagram only for the conservative case.

Stellar models with mass loss by [33] evolve at lower luminosities and cover a narrower region of effective temperatures compared to evolution with constant mass.

In this case, evolutionary tracks move to the right of the HR-diagram. For mass losing stars, as their central hydrogen abundance becomes very low, the stars contract and the tracks move leftward in the HR-diagram. In the presence of strong mass loss, this motion continues until central hydrogen burning has finished. In the models by [34] the locus of points describing the onset of core He-burning tend towards lower $T_{\rm eff}$ at increasing stellar masses. During the evolution the luminosity is almost constant.

The He-burning phase takes place in different regions of the HR-diagram, depending on stellar mass and mass loss. Models with $120M_{\odot} \leq M \leq 750M_{\odot}$ are able to reach their ZAMS line, at typical effective temperatures log $T_{\rm eff} = 3.6 - 3.8$, where they remain up to central carbon ignition.

In the present models, evolutionary tracks describe different paths on the HR-diagram depending on stellar mass and mass loss rates. Galactic and pregalactic Population III mass losing stars move from the left to the right in the upper part of the HR-diagram. The luminosity and temperature decreases with high mass-loss rates. For mass-loss parameters $N = 50$, 100 and 200, they reach the red giant region with $\log T_{\rm eff} \sim 3.6$.

For N=50, the luminosity of galactic Population III stars increases and the effective temperature reduces at the beginning of H-burning, then stars evolve with practically constant luminosity and decreasing effective temperature during H- and He-burning. At the end of this last phase, the luminosity decreases with the effective temperature but then suddenly increases just before C-ignition.

For galactic stars with N=100, the luminosity is almost constant during H- and He-burning, while for pregalactic stars, the luminosity decreases during He-burning. Both, galactic and pregalactic stars reaches the red giant region, with typical effective temperatures and a sharp increase in luminosity by the end of the He-burning phase.

For high mass-loss parameters, evolutionary tracks for galactic and pregalactic stars are similar only during H-burning. These tracks are characterized by a strong decrease in luminosity depending upon the mass-loss rate. At the beginning of H-burning, galactic and pregalactic stars descends along the red giant region but then evolve with constant luminosity and decreasing effective temperature. During He-burning the behavior is different. With N=200, the luminosity is constant for galactic stars but decreases for pregalactic stars. At the end of He-burning, their luminosity increases with constant effective temperature. After a relatively short time, the effective temperature increases up to

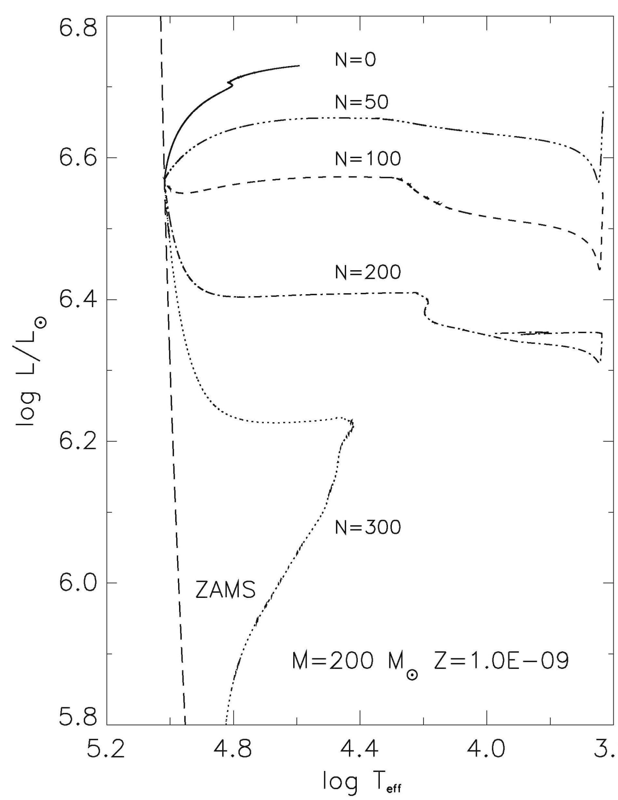

FIGURE 1. Evolutionary tracks in the HR-diagram for $200M_{\odot}$ pregalactic stars with metallicity $Z = 10^{-9}$ and mass loss parameters $N = 0, 50, 100, 200$ and 300 during the hydrogen, and helium burning phases. The Zero Age Main Sequence (ZAMS) line is shown.

log $T_{\rm eff}$=3.8−4.0 with constant luminosity, and the stars move to the left of the HR-diagram.

With strong mass-loss rates, N=300, evolutionary tracks are different for galactic and pregalactic stars. In the first case, the luminosity decreases during He-burning and the temperature increases with constant luminosity, so stars invert their movement in the HR-diagram. In the case of pregalactic stars, at the beginning of He-burning, their luminosity decreases slightly, but then evolves with high effective temperatures.

As a consequence of their high mass-loss rates, stars have lost appreciable amounts of mass. In fact, by this time, the stellar masses have been reduced to the massive star range. A feature is observed when their luminosity is decreasing and the effective temperature is increasing: stars move now to the left in the HR-diagram. In their evolutionary tracks, pregalactic stars evolving with strong mass loss move along the zone of the luminous blue variables reaching the Wolf-Rayet phase. In these cases, stars evolve below the so-called Humphreys-Davidson (HD) limit at the left upper part of the HR-diagram descending in luminosity along the ZAMS line.

5. Discussion

5.1. Effect of metallicity

The principal effects of low metallicity on the presupernova structure are related to the diminished mass loss [35]. Presupernova stars of lower metallicity have significantly different characteristics than metal enriched stars, at least for high mass. However, the mass loss rate for lower metallicity stars is uncertain.

5.2. Is it possible to avoid PISNe?

For the present work, galactic and pregalactic Population III stars develop helium core masses depending on their initial mass and mass loss rates. For $200M_\odot$ galactic Population III mass losing stars with mass loss parameter N=50 and metallicity $Z = 10^{-6}$, their convective core size is $q_{\rm cc} = 0.48$ and their helium core mass is $M_{\rm He} = 80.95M_\odot$, where $q_{\rm cc}$ is the ratio of the convective core mass to the total mass of the star. The same case but for pregalactic stars with $Z = 10^{-6}$ implies that $q_{\rm cc} = 0.50$ and $M_{\rm He} = 84.45M_\odot$. In this case we have $q_{\rm cc} = 0.29$ and $M_{\rm He} = 48.14M_\odot$.

Then the final fate of these $200M_\odot$ mass losing stars may be a pair-instability supernovae explosion. In all studied cases, the stars develop a helium core with mass enough to encounter the pair instability. However, $100M_\odot$ galactic and pregalactic stars, and mass losing VMSs with high mass loss rates, could explode like hypernovae.

6. Comparison with other works

Very massive *first stars* seed their own halos and possibly enrich the interstellar medium by releasing metals from PISNe in stars with ZAMS in the mass range $140 - 260M_\odot$ [12]. This point has been criticized by [22]. Other authors argue that the relative metal abundances in EMP halo stars match the expected signatures of VMSs [26,36]. However, [37] considered that these observed abundances are better matched by core-collapse supernovae or HNe from 10 to $50M_\odot$ progenitors.

Tumlinson, Venkatesan and Shull distinguished two versions of the VMS hypothesis [22]. The *strong* hypothesis implies that the first generation was exclusively VMSs; while in the *weak* hypothesis the first generation included VMSs in addition to $M \leq 50M_\odot$ stars. A "prompt" (P) inventory of Fe by an initial population of stars with large Fe yields but little or no *r*-elements ($A > 100$) was proposed [38].

However, VMSs have no significant post-He nuclear burning and therefore produce no *r*-elements [12]. Progenitors with $M = 8 - 40M_\odot$ are needed in the first generation to provide the observed *r*-process elements [39]. Comparison of the observed abundances with theoretical yields for VMSs pair-instability supernovae from $M = 140 - 260M_\odot$ show that VMSs of a single mass cannot explain the observed yields. An alternative explanation for EMP metal abundances have been developed by [18, 20, 21, 37]. They argued that energetic supernovae or hypernovae with energies $E_{51} = 10 - 100$, could be relevant for early nucleosynthesis at low metallicity. In their models, [37] estimated nucleosynthesis by HNe from zero-metallicity progenitors with $M < 140M_\odot$.

Nomoto et al. proposed that the first generation of supernovae was composed of $\sim 20 - 130M_\odot$ supernovae which can well account for the abundance pattern of EMP stars [18]. These patterns cannot be explained by the explosions of $130 - 300M_\odot$ stars which undergo PISNe and are disrupted completely [12, 20, 40].

In the models presented here, the stars develop large convective cores, for 100, 200 and $300M_\odot$ with $Z = 10^{-6}$, their masses during hydrogen burning are $M_{\rm He} = 40$, 89 and 140 $M_\odot$, respectively, and during helium burning are $M_{\rm C}$=33, 64 and $117M_\odot$, respectively. For the same masses, pregalactic stars with $Z = 10^{-9}$ form a convective core of $M_{\rm He} = 39$, 89 and 134 $M_\odot$ during hydrogen burning and $M_{\rm C} = 39$, 86 and $132M_\odot$ during helium burning. That is, pregalactic Population III stars develop helium cores which can disrupt the stars. In the initial mass range from 100 to $300M_\odot$, stars could explode like supernovae. Only stars with $M > 300M_\odot$ could develop a helium core $M_{\rm He} \gtrsim 140M_\odot$ and will collapse directly into a black hole.

Our models calculated for $100M_\odot$ galactic and pregalactic Population III stars with metallicities Z=$10^{-6}, 10^{-9}, 10^{-10}$ form helium cores of 40, 38 and $32M_\odot$, respectively, for the conservative case, and 39, 38 and $30M_\odot$, respectively, for a moderate mass-loss rate. Their carbon-oxygen core masses are 35, 37 and $30M_\odot$ in the conservative case, and 39, 35 and $30M_\odot$ for mass losing stars with a mass loss parameter $N = 50$. Then, these stars could explode like hypernovae.

On the other hand, with high mass loss rates, galactic and pregalactic $200M_{\odot}$ stars reduce their masses to about 100 or less $M_{\odot}$. Their helium core masses are in the range of $25-50M_{\odot}$, and their carbon-oxygen core masses are between $15-46M_{\odot}$. With these He- and CO-cores, stars likely explode like hypernovae.

7. Conclusions

Massive and very massive galactic and pregalactic stars with $M{<}130M_{\odot}$ could explode like hypernovae.

Stars with $100M_{\odot}{<}M{<}140M_{\odot}$ do not explode as SNe but collapse into black holes [12]. For the present work, $100M_{\odot}$ galactic and pregalactic stars develop $M_{\rm He}\sim 40$, 38, and $32M_{\odot}$ in the conservative case ($N{=}0$), and $M_{\rm He}{\sim}39$, 27 and $30M_{\odot}$ with a moderate mass loss rate ($N{=}50$). Then, in both cases, with and without mass loss, they would collapse into black holes.

However, according to scenarios by [18, 20, 21, 37, 40], the studied stars here presented ($M{<}130M_{\odot}$) both evolving without and with mass loss could explode like hypernovae. More massive stars (*e.g.* $M{=}200M_{\odot}$), if they lose mass with high mass loss rates, can reduce appreciably their initial mass during the H-, and He-burning, forming He-cores with masses in the $25{-}50M_{\odot}$ range, and CO-cores in the $15{-}46M_{\odot}$ range. These cores could also explode like hypernovae. This is interesting because hypernovae could have made an important contribution to the early galactic (and cosmic) chemical evolution.

Acknowledgments

This work has been partially supported by the Mexican Consejo Nacional de Ciencia y Tecnología (CONACyT), and the German Deutscher Akademischer Austauschdienst (DAAD). One of us (D.B.) thank CONACYT for financial support. The calculations for this paper were performed by computer system in the Institute of Astronomy of the Academy of Sciences, Czech Republic, the Instituto Nacional de Investigaciones Nucleares (Draco), the Universidad Nacional Autónoma de México (Kambalam) and the Universidad de Sonora (Mezquite).

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