EVOLUTION OF THE FIRST STARS WITH DARK MATTER BURNING

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ABSTRACT

Recent theoretical works have revealed the possibly important role of the capture and annihilation process of weakly interacting massive particles (WIMPs) for the first stars. Using new evolutionary models of metal-free massive stars, we investigate the impact of such “dark matter burning” for the first stars in different environments of dark matter (DM) halos, in terms of the ambient WIMP density (ρs). We find that, in agreement with existing literature, stellar lifetimes can be significantly prolonged for a certain range of ρs (i.e., 10 10 ≤ ρs [GeV cm −3] ≤ 10 11 with the current upper limit for the spin-dependent elastic scattering cross section σ SD 0 = 5 × 10 39 cm 2). This greatly enhances the role of rotationally induced chemical mixing in rotating stars, in favor of abundant production of primary nitrogen, massive helium stars, and long gamma-ray bursts, from the first stars. We also find that stars with ρs > 2 × 10 11 GeV cm −3 may not undergo nuclear burning stages, confirming the previous work, and that ionizing photon fluxes from such DM supported stars are very weak. Delayed metal enrichment and slow reionization in the early universe would have resulted if most of the first stars had been born in DM halos with such high ρs, unless it had been lowered significantly below the threshold for efficient DM burning on a short timescale.

Subject headings: dark matter — early universe — stars: evolution — stars: rotation

Online material: color figures

1 INTRODUCTION

In the current framework of the ΛCDM cosmological model, the possibility that dark matter (DM) annihilation effects may impact stellar evolution has recently received renewed attention. After the original works of Bouquet, Dearborn, Freese, Gould, Griest, Krauss, Olive, Press, Raffelt, Renzini, Salati, Silk, Spurgel, Srednicki, and Wilczek in the 1980s and early 1990s, several authors have recently reexamined the effects that DM, if made of weakly interacting massive particles (WIMPs), would have on compact objects (Moskalenko & Wai 2007; Bertone & Fairbairn 2008) and on the zero-age main sequence of low-mass stars (Fairbairn et al. 2008). This exciting activity has been motivated by a double scope: any peculiar and distinguishable feature of WIMP annihilation on observable stellar quantities is extremely precious for “quest” for dark matter evidence; on the other hand, all possible effects impacting the life of celestial objects must be taken into account by astrophysicists in the current precision era.

In particular, the first stellar episode at high redshift occurs under very different conditions from those in the present universe. The higher concentration of dark matter, the short Hubble time which prevents DM self-annihilation from severely affecting the central density, and the characteristic formation of a single Population III star in the center of the halo are the most favorable conditions for DM annihilation effects to be very efficient in the first stars. In their pioneering work, Spolyar et al. (2008) first found the possibility of very high DM density in primordial halos at high redshift to such an extent that energy released from DM annihilation at the center may halt the gravitational collapse of the baryonic cloud, calling such a DM-powered object a dark star. Iocco (2008) and Freese et al. (2008c) also noticed that WIMP capture is most efficient in Population III stars. More recently, Freese et al. (2008a, 2008b) and Iocco et al. (2008) further investigated the role of annihilation of adiabatically contracted DM in the formation of the first stars. Iocco et al. (2008) have also followed the evolution from the pre–main-sequence phase to helium exhaustion in the presence of WIMP capture and annihilation (hereafter, DM burning), showing that this can severely delay the evolution of pre-MS objects in the early universe, as well as extend their MS lifetimes.

All of these studies motivate us to explore possible consequences of DM burning for the final fate of the first stars and their feedback effects on the evolution of the early universe, even if the role of DM annihilation in the formation of the first stars still remains subject to many uncertainties (see O’Shea et al. 2008 for a recent review). In this Letter, we address the issue by discussing the evolution of the first stars of 20 ≥ M/M ∗ ≤ 300 up to the carbon burning stage (§ 2). We also investigate the interplay of rotation with DM burning in the evolution of the first stars of 100 M/M ∗, given the particular importance of rotation for the evolution and deaths of metal-poor massive stars (e.g., Meynet et al. 2008; Yoon et al. 2008). Implications of our results for the history of reionization in the early universe are briefly discussed (§ 3).

2 PHYSICAL ASSUMPTIONS AND RESULTS

We have implemented the DM capture and annihilation process in a hydrodynamic stellar evolution code, following Gould (1987). The DM capture rate C, is calculated using Gould’s equations as reported in equations (1) and (2) of Iocco (2008). Throughout this Letter we assume the DM-baryon scattering cross section σ 0 is 5 × 10 39 cm 2 for the spin-dependent scattering, to which only hydrogen is sensitive, and 10 43 cm 2 for the spin-independent one. These correspond to the current upper limits of WIMP direct detection search (Desai et al. 2004; Angle et al. 2008). We adopt the same values for other parameters as those used in Iocco (2008) to calculate C, except for the ambient DM density (see below). The WIMPs captured by a star eventually reach thermal equilibrium with the gas, in a configuration dictated by the gravitational potential: the consequent DM density can be given by

\[ \rho_s = \frac{\dot{m}_s}{H^2}, \]

where \( H \) is the Hubble constant and \( \dot{m}_s \) is the mass accretion rate. The WIMPs then start annihilating and the energy released is used to heat the gas, expanding the halo and increasing the DM density. The energy released from annihilation is given by

\[ E = \frac{1}{2} m_p c^2 \frac{\dot{m}_s}{H^2}, \]

where \( m_p \) is the proton mass. The temperature of the gas, \( T_g \), and the DM density, \( \rho_s \), are temperature and density at the stellar center, \( c \) and \( k \),...
Fig. 1.—Top: H-R diagram of the nonrotating first star models on the ZAMS of different masses for different adopted values of $\sigma_0^\text{DM} \rho_0$ as indicated by the labels. Here $\sigma_0^\text{DM}$ is the spin-dependent WIMP scattering cross section, and $\rho_0$ is the ambient WIMP density. Stars in the gray shaded region are supposed to be only powered by DM burning, without nuclear reactions (i.e., $T_e < 10^7$ K). We use $\sigma_0^\text{DM} = 5 \times 10^{-36}$ cm$^2$. Bottom: Lifetimes of the nonrotating first stars as a function of the initial mass for different values of $\sigma_0^\text{DM} \rho_0$ (in the unit of cm$^{-3}$). These lifetimes are obtained from stellar models up to carbon burning for $\rho \leq 10^5$ GeV cm$^{-3}$ (i.e., $\sigma_0^\text{DM} \rho_0 \leq 0.02 \times 10^{-26}$ GeV cm$^{-3}$), while only approximate estimates are given for $\rho \geq 10^5$ GeV cm$^{-3}$ (i.e., $\sigma_0^\text{DM} \rho_0 \geq 0.05 \times 10^{-26}$ GeV cm$^{-3}$). [See the electronic edition of the Journal for a color version of this figure.]

are the speed of light and Boltmann’s constant, respectively. The energy generation rate due to DM annihilation is given by

$$\epsilon_\gamma(r) = \frac{2}{3} \langle \sigma v \rangle n_\gamma^2(r) m_\gamma \text{[erg cm}^{-3} \text{s}^{-1}]$$

(1)

where $m_\gamma$ is the mass of the DM particle; we assume it to be $m_\gamma = 100$ GeV, which is often taken as a fiducial value in astrophysical studies for DM search. We use $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^{-3}$ s$^{-1}$, the value best fitting the relic DM abundance (see, e.g., Bertone et al. 2005 for a recent review). The factor $2/3$ is to consider that part of the energy is carried away by neutrinos. We consider the time-dependent evolution of the total number of WIMPs ($N_{\text{tot}}$) in the star, and the number of thermally relaxed WIMPs in the core ($N_{\text{th}}$) by the following equations in order to normalize $n(r)$:

$$\frac{dN_{\text{tot}}}{dt} = C_n - \int n(r)^2 \langle \sigma v \rangle dV,$$

(2)

$$\frac{dN_{\text{th}}}{dt} = \Gamma_{\text{th}} - \int n(r)^2 \langle \sigma v \rangle dV,$$

(3)

where $\Gamma_{\text{th}}$ is the thermalization rate that can be approximated by

$$\Gamma_{\text{th}} = \frac{N_{\text{tot}} - N_{\text{th}}}{\tau_{\text{th}}}, \quad \tau_{\text{th}} = \frac{4 \pi}{3} \frac{m_\gamma}{2G} \frac{R^{5/2}}{\sigma_0 M^2}.$$

(4)

See Iocco et al. (2008) for detailed discussion on the thermalization timescale $\tau_{\text{th}}$. Our models show that equilibrium between $C_n$ and $\Gamma_{\text{th}}$ is well maintained up to the core helium burning phase (see Fig. 2 below).
We consider several different values for the ambient DM energy density \( \rho_b \) ranging from 0 to \( 2 \times 10^{12} \) GeV cm\(^{-3} \). For the initial composition of the first stars, we assume the mass fractions of \(^1\)H, \(^4\)He, and \(^3\)He to be 0.76, 0.23999, and 0.00001, respectively. The mass-loss rate from metal-free stars is assumed to be 0.1 km s\(^{-1} \), which corresponds to 10% of the Keplarian value. [See the electronic edition of the Journal for a color version of this figure.]

No meaningful change in the stellar structure according to different values of \( \rho_b (\ll \rho_{\text{crit}}) \) is observed in nonrotating models. Since DM burning only occurs within a very small radius \( r_b (\ll R_{\text{core}}) \), stars with different \( \rho_b \) at a given mass have similar amounts of energy flux from the core and produce helium cores of a similar size (e.g., \(~40 \, \odot\) from 100 \( \odot\) stars). The luminosity resulting from DM burning gradually increases early on the main sequence as the star expands, but continuously decreases in later stages since the significant reduction of the number of hydrogen atoms lowers the DM capture rate. Rapid increase of the stellar radius after helium exhaustion makes the thermalization time very long, leading to reduction of the number of thermalized WIMPs (see Fig. 2). The DM luminosity accordingly decreases further from \( 7 \times 10^5 \, L_\odot \) to about \( 10^4 \, L_\odot \) during the carbon burning phase, in the given example with 100 \( \odot\) (Fig. 2). Carbon burning and particularly neutrino cooling \( (L_\nu > 10^{10} \, L_\odot) \) dominate the evolution at this stage as shown in Figure 2. As the evolution of the star beyond carbon exhaustion should also be governed by neutrino cooling and other nuclear reactions such as oxygen burning, the effect of DM burning on the presupernova structure must be minor. As the situation remains similar in the other models of \( 20 \leq M/\odot \leq 300 \), we conclude that DM burning may not change the final fate of the nonrotating first stars.

It is noteworthy, however, that rotation can dramatically change the evolution with DM burning. Fluids in rotating massive stars are subject to various rotationally induced hydrodynamic instabilities such as Eddington-Sweet circulations, which can cause mixing of chemical species across the boundary between the hydrogen burning core and the radiative envelope. Such mixing is usually stabilized by the strong buoyancy potential due to the chemical stratification between the hydrogen burning core and the envelope. However, if chemical mixing can occur faster than the building-

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**TABLE 1**

| \( v_{\text{rel}}/v_k \) (GeV cm\(^{-1} \)) | \( N_{\text{H}} \) | \( N_{\text{He}} \) | Duration (Myr) |
|---|---|---|---|
| 0.0 | 0.00 | 1.2 \times 10^8 | 2.2 \times 10^2 | 3.2 |
| 0.0 | 2 \times 10^{10} | 2.1 \times 10^6 | 3.4 \times 10^2 | 5.5 |
| 0.0 | 4 \times 10^{10} | 8.5 \times 10^6 | 1.5 \times 10^3 | 22.3 |
| 0.0 | 10^{10} | 2.9 \times 10^6 | 6.3 \times 10^3 | 100.0 |
| 0.0 | 2 \times 10^4 | 2.0 \times 10^8 | 1.7 \times 10^4 | 100.0 |
| 0.0 | 2 \times 10^{10} | 1.3 \times 10^2 | 9.4 \times 10^3 | 100.0 |
| 0.1 | 0.00 | 1.5 \times 10^8 | 2.5 \times 10^2 | 3.4 |
| 0.1 | 2 \times 10^{10} | 2.7 \times 10^4 | 5.2 \times 10^2 | 6.0 |
| 0.1 | 4 \times 10^{10} | 8.7 \times 10^8 | 3.8 \times 10^3 | 19.6 |

* The numbers are calculated only for the first 100 Myr.

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For a given \( \rho_b \), our models give longer lifetimes than those by Iocco et al. (2008). This is because these authors used an approximation for the DM capture rate \( C_b \), while we integrate eq. (2) of Iocco (2008) over the entire stellar structure.
up of chemical gradients by nuclear burning (i.e., $\tau_{\text{mix}}/\tau_{\text{mix}} < 1$), then (quasi-) chemical homogeneity can be maintained on the main sequence (so-called chemically homogeneous evolution) (Maeder 1987). The condition $\tau_{\text{mix}}/\tau_{\text{mix}} < 1$ can be met either by reducing $\tau_{\text{mix}}$ or increasing $\tau_{\text{mix}}$. Rapid rotation tends to do the former, and we find that DM burning tends to do the latter. This is because the mixing timescale due to Eddington-Sweet circulations remains almost unchanged with increasing $\rho_\phi$ (for $\rho_\phi < \rho_\phi^{\text{crit}}$), while the nuclear burning timescale increases due to the DM burning. This explains the remarkable impact of DM burning in the evolution of our rotating models as shown in Figure 3. As shown in the top panel, rotation in this model ($\rho_\phi/\rho_\phi^{\text{crit}} = 0.1$) is not rapid enough to cause the strong mixing by itself without DM burning. With $\rho_\phi = 4 \times 10^{10}$ GeV cm$^{-3}$ (see bottom panel), however, the 100 $M_\odot$ star lives about 10 times longer than in the corresponding non-DM burning case, and the star undergoes the quasi-chemically homogeneous evolution even with slow initial rotation because of the DM burning effect on nuclear burning timescale (cf. Yoon et al. 2006). The star is thus gradually transformed into a massive helium star by the end of main sequence as almost all of the hydrogen atoms in the star are fused into helium atoms due to mixing.

3. DISCUSSION

Our results indicate that DM burning should not significantly alter our view on the final fate of the nonrotating first stars: pair-instability supernova for $140 \leq M/M_\odot \leq 260$, and core-collapse events for other masses (Heger & Woosley 2002), although their lifetimes may be significantly prolonged. However, the impact of DM burning appears more important for rotating stars. The quasi-chemically homogeneous evolution can be rather easily realized even with moderate rotation velocities with $10^{10} \leq \rho_\phi$ [GeV cm$^{-3}$] $\leq 10^{11}$. Such evolution can lead to production of massive helium stars that emit large amounts of helium ionizing photons, as well as abundant production of primary nitrogen, as discussed in Yoon et al. (2008). Note also that the quasi-chemically homogeneous evolution scenario (CHES) is one of the favored ones for the production of long GRBs from metal poor stars (Yoon & Langer 2005; Woosley & Heger 2006). Our result therefore indicates that DM burning might promote the production of long gamma-ray bursts from the first stars of $12 \leq M/M_\odot \leq 60$ via the CHES channel (see Yoon et al. 2006).

DM burning in the first stars must have consequences in the history of reionization in the early universe. Table 1 lists the number of hydrogen and helium ionizing photons emitted from 100 $M_\odot$ models. If $\rho_\phi \leq 2 \times 10^{11}$ GeV cm$^{-3}$, the total number of ionizing photons increases proportionally to the DM density, as a direct consequence of the life-prolonging effect of DM burning. For a given $\rho_\phi$ rotation does not significantly alter hydrogen ionizing photon counts nor the lifetime. However, for models that take path of the CHES, the helium ionizing photon counts is increased by more than a factor of 2 compared to the nonrotating case. If $\rho_\phi$ is very large, on the other hand, the surface temperature of the star drops significantly enough (Fig. 1) that the total number of ionizing photons is reduced even with much longer lifetimes due to the DM burning. For example, with $\rho_\phi = 2 \times 10^{12}$ GeV cm$^{-3}$, it would have to take $\gtrsim 10$ Gyr to emit as many hydrogen ionizing photons as a non-DM burning counterpart. Therefore, if most of the first stars had been born with such high $\rho_\phi$, their contribution to reionization would have been dramatically reduced. The effect of the temperature drop on the number of helium ionizing photons is even more prominent: with $\rho_\phi = 2 \times 10^{12}$ GeV cm$^{-3}$, it decreases by more than 19 orders of magnitude compared to the other cases with lower $\rho_\phi$. Future study on the history of helium ionization at high redshift might therefore be a strong probe of DM burning in the first stars.

In this study we assume that the background DM halo density stays constant throughout the stellar evolution. This assumption may be valid if the stellar lifetimes are shorter than about 100 Myr—which is the expected merger timescale of DM halos at $z \sim 20$ (e.g., Lacey & Cole 1993) — as in our model sequences with $\rho_\phi \leq 4 \times 10^{10}$ GeV cm$^{-3}$. The evolution of DM burners in halos with higher $\rho_\phi$, however, should be critically determined by the change of DM halo environments. If $\rho_\phi$ is sufficiently reduced due to merger events and/or to displacement of the star from the densest region of the DM halo, the DM burners will become “normal” stars, dominated by nuclear burning. The star may then die quickly as we expect for normal stars, or become a “born again” DM burner if $\rho_\phi$ increases again in later stages for some reason. The detailed history of the feedback from the first stars (e.g., metal enrichment and reionization) on the evolution of the early universe may depend on the nature and evolution of DM halos where the first stars are formed. This issue should be addressed in future work.

As a note added in proof, we wish to acknowledge that Taoso et al. (2008) independently report similar results about the effect of DM burning on the MS lifetime and some stellar properties, using a different numerical code. S. A. is supported by a Department of Energy contract to SLAC DE-AC3-76SF00515. F. I. is supported by MIUR through grant PRIN-2006. S. C. Y. is supported by the DOE SciDAC Program (DOE DE-FG02-06ER41438).

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