Dark matter annihilations in Population III stars

Marco Taoso,[1,2] Gianfranco Bertone,[2] Georges Meynet,[3] and Silvia Ekström[3]

[1]*INFN, Sezione di Padova, via Marzolo 8, Padova, 35131, Italy*

[2]*Institut d'Astrophysique de Paris, UMR 7095-CNRS, Université Pierre et Marie Curie, 98 bis Boulevard Arago 75014, Paris, France*

[3]*Geneva Observatory, University of Geneva, Maillettes 51, 1290 Sauverny, Switzerland*

We study the impact of the capture and annihilation of weakly interacting massive particles (WIMPs) on the evolution of Population III stars. With a suitable modification of the Geneva stellar evolution code, we study the evolution of 20 and $200 M_\odot$ stars in dark matter halos with densities between 10^8 and 10^{11} GeV/cm^3 during the core H-burning phase, and, for selected cases, until the end of the core He-burning phase. We find that for WIMP densities higher than $5.3 \times 10^{10} (\sigma_p^{\rm SD}/10^{-38} {\rm cm}^2)^{-1}$ GeV cm^{-3} the core H-burning lifetime of $20 M_\odot$ and $200 M_\odot$ stars exceeds the age of the Universe, and stars are sustained only by WIMP annihilations. We determine the observational properties of these "frozen" objects and show that they can be searched for in the local Universe thanks to their anomalous mass-radius relation, which should allow unambiguous discrimination from normal stars.

In the standard cosmological model, the matter density of the Universe is dominated by an unknown component, approximately 5 times more abundant than baryons, dubbed dark matter (DM). Among the many DM candidates proposed in the literature, weakly interacting massive particles (WIMPs), i.e. particles with mass $\mathcal{O}(100)$ GeV and weak interactions, appear particularly promising, also in view of their possible connection with well motivated extensions of the standard model of particle physics (see Ref. [1] for recent reviews on particle DM, including a discussion of ongoing direct, indirect, and accelerator searches). Despite their weak interactions, WIMPs can lead to macroscopic effects in astrophysical objects, provided that they have a sizeable scattering cross section off baryons. In this case, in fact, DM particles traveling through stars can be captured and sink at the center of the stars. Direct searches and astrophysical arguments, however, severely constrain the strength of DM-baryons interactions (see e.g. Ref. [2] and references therein). Since the capture rate is proportional to the product of the scattering cross section times the local DM density, large effects are thus expected in regions where the DM density is extremely high (this was already noticed in the context of the so-called "cosmions" [3]). Recent progress in our understanding of the formation and structure of DM halos has prompted a renewed interest in the consequences of DM capture in stars, in particular, in the case of white dwarfs [4], compact objects [5], and main sequence stars [6] at the Galactic center, where the DM density could be extremely high [7].

Alternatively, one may focus on the first stars, which are thought to form from gas collapsing at the center of 10^6–$10^8 M_\odot$ DM halos at redshift $z \lesssim 10$–30. The consequences of DM annihilations in Pop III stars were first investigated by Spolyar, Freese, and Gondolo [8], who have shown that the energy released by WIMP annihilations in these mini-halos, during the formation of a proto-

star, may exceed any cooling mechanism, thus leading to a new phase of stellar evolution (see also Ref. [9]). The formation of proto-stars with masses between $6 M_\odot$ and $600 M_\odot$ in DM halos of $10^6 M_\odot$ at $z = 20$ can actually be delayed by $\sim 10^3$–10^4 yrs [10]. It was subsequently shown in Refs. [11,12], that the annihilation of DM particles captured at the center of the star, due to scattering off the stellar nuclei, can lead to an energy injection that overwhelms nuclear reactions. Under these circumstances, the core H-burning phase of Pop III stars, in DM halos of density of 10^{11} GeV cm^{-3}, is substantially prolonged, especially for small mass stars ($M_* < 40 M_\odot$) [10].

In this paper, we perform a detailed study of the impact of DM capture and annihilation on the evolution of Pop III stars implementing in the Geneva stellar evolution code [13] a WIMP luminosity term as described below. With respect to previous analyses, this already allows us to properly take into account the stellar structure in the calculation of the capture rate that we compute, following Ref. [14], as

$$C = 4\pi \int_0^{R_*} dr\, r^2 \frac{dC(r)}{dV} \qquad (1)$$

with

$$\frac{dC(r)}{dV} = \left(\frac{6}{\pi}\right)^{1/2} \sigma_{\chi,N} \frac{\rho_i(r)}{M_i} \frac{\rho_\chi}{m_\chi} \frac{v^2(r)}{\bar{v}^2} \frac{\bar{v}}{2\eta A^2}$$

$$\times \left\{ \left(A_+ A_- - \frac{1}{2}\right)[\chi(-\eta, \eta) - \chi(A_-, A_+)] \right.$$

$$\left. + \frac{1}{2}A_+ e^{-A_-^2} - \frac{1}{2}A_- e^{-A_+^2} - \frac{1}{2}\eta e^{-\eta^2}\right\},$$

$$A^2 = \frac{3v^2(r)\mu}{2\bar{v}^2 \mu_-^2}, \qquad A_\pm = A \pm \eta, \qquad \eta^2 = \frac{3v_*^2}{2\bar{v}^2}$$

$$\chi(a, b) = \frac{\sqrt{\pi}}{2}[\mathrm{Erf}(b) - \mathrm{Erf}(a)] = \int_a^b dy\, e^{-y^2},$$

$$\mu_- = (\mu_i - 1)/2, \qquad \mu_i = m_\chi/M_i, \qquad (2)$$

where $\rho_i(r)$ is the mass density profile of a given chemical element in the interior of the star and M_i refers to its atomic mass, while ρ_χ, m_χ, and $\bar{v}$ are, respectively, the WIMP mass and the WIMP density and velocity dispersion at the star position. The velocity of the star with respect to an observer, labeled as v_*, is assumed to be equal to $\bar{v}$, giving therefore $\eta = \sqrt{3/2}$. The radial escape velocity profile depends on $M(r)$, i.e. the mass enclosed within a radius r, $v^2(r) = 2 \int_r^\infty GM(r')/r'^2 dr'$. The WIMP scattering cross section off nuclei, $\sigma_{\chi,N}$, is constrained by direct detection experiments and for a WIMP mass of 100 GeV the current upper limits are $\sigma_{SI} = 10^{-43}$ cm^2 [15] and $\sigma_{SD} = 10^{-38}$ cm^2 [16], respectively, for spin-independent and spin-dependent WIMP interactions off a proton. We will adopt these reference values throughout the paper, but the capture rate can be easily rescaled for other scattering cross sections by using Eq. (3). The spin-independent interactions with nucleons inside nuclei add up coherently giving an enhancement factor A^4 with respect to the interaction with a single nucleon: $\sigma_{\chi,N}^{SI} = A^4 \sigma_{\chi,p}$, where A is the mass number. There is no such enhancement for the spin-dependent interactions. We consider the contribution to the capture rate from WIMP-hydrogen spin-dependent interactions and WIMP-helium ^{4}He spin-independent interactions, neglecting the presence of other elements because of their very low abundance. The contribution of helium, for the WIMPs parameters above, is found to be negligible with respect to that from hydrogen.

Once captured, WIMPs get redistributed in the interior of the star reaching, in a characteristic time τ_{th}, a thermal distribution [17]:

$$n_\chi(r) = n_0 e^{(-r^2)/(r_\chi^2)} \quad \text{with} \quad r_\chi = \sqrt{\frac{3kT_c}{2\pi G\rho_c m_\chi}} \quad (3)$$

with T_c and ρ_c referring to the core temperature and density. The distribution results are quite concentrated toward the center of the star: e.g. for a $20M_\odot$ star immersed in a WIMP density of $\rho_\chi = 10^9$ GeV cm^{-3} at the beginning of the core H-burning phase we obtain $r_\chi = 2 \times 10^9$ cm, a value much lower than the radius of the star, $R_* = 10^{11}$ cm. This consideration underlines the importance of an accurate spatial resolution in the core to properly treat the luminosity produced from WIMPs annihilations. We have also checked that regardless of the extremely high concentrations of WIMPs obtained at the center of the stars, the gravity due to WIMPs is completely negligible. The number of scattering events needed for DM particles to thermalize with the nuclei in the star is of order $\approx m_\chi/M_H$, thus an upper limit on the thermalization time can be obtained as $\tau_{th} = (m_\chi/M_H)/(\sigma_{SD}\bar{n}_H\bar{v})$ where $\bar{n}_H$ is the average density on the star.

The WIMPs emissivity is $\epsilon_\chi(r) = 4\pi(\sigma v)m_\chi c^2 n_\chi^2(r)$ and the total WIMPs luminosity, L_χ, is simply the integral over the volume of the star. For the annihilation cross

section times relative velocity (σv), we assume the value 3×10^{-26} cm^2, as appropriate for a thermal WIMP, but note that the total WIMP luminosity at equilibrium does not depend on this quantity. After a time $\tau_\chi = \sqrt{C(\sigma v)\pi^{-3/2}r_\chi^{-3}}$ an equilibrium between capture and annihilation is established, and this incidentally allows to determine the normalization constant n_0 above.

We have checked that the two transients τ_χ and τ_{th} remain much smaller, during the evolution of the star, than the Kelvin-Helmotz time scale τ_{KH} and the time scale needed for the nuclear reactions to burn a small hydrogen fraction, e.g. $\Delta X_c = 0.002$, of the convective core, τ_{nucl}:

$$\tau_{KH} = \frac{GM_*^2}{R_*L_*}, \qquad \tau_{nucl} = \frac{q_c\Delta X_c M_*0.007c^2}{L_*},$$

where the $*$ labels quantities relative to the star and q_c is the core convective mass fraction. This argument justifies the assumption of equilibrium between capture and annihilation and the use of the radial distribution in Eq. (3). We assume here an average WIMP velocity $\bar{v} = 10$ Km s^{-1}, the virial velocity in a halo of 10^5–$10^6 M_\odot$ at $z = 20$ (see [11] and references therein). As for the DM density, semi-analytic computations of the adiabatic contraction of DM halos [8], in agreement with the results extrapolated from simulations of first star formation [18], suggest DM densities of order 10^{12} GeV cm^{-3} or even higher.

We have implemented the effects of WIMPs annihilation in the Geneva stellar evolution code (see Ref. [13] for details) and followed the evolution of $20M_\odot$ and $200M_\odot$ stars for different DM densities. We show in Fig. 1 the evolutionary tracks for the $20M_\odot$ model, and show for comparison (black line) the case of a standard Pop III star without WIMPs. For DM densities smaller than 10^9 GeV cm^{-3} the evolutionary tracks closely follow that of a normal star and they are not shown for simplicity. The position of the star at the beginning of the core H-burning phase (zero-age main sequence, or ZAMS) is obtained when, after a short transient, the luminosity produced at the center of the star equals the total luminosity and the star settles down in a stationary regime. For increasing DM densities the WIMPs luminosity produced at the center overwhelms the luminosity from nuclear reactions and makes the star inflate, producing therefore a substantial decrease of the effective temperature and a moderate decrease of the star luminosity at the ZAMS position, with respect to the standard scenario. For $\rho_\chi = 10^{10}$ GeV cm^{-3}, the energy produced by WIMPs present in the star at a given time, estimated as $E_\chi \simeq L_\chi\tau_{KH}$, is, at the ZAMS, ~0.8 times the gravitational potential energy of the star, and the star therefore starts to contract. In this phase, the core temperature, and consequently also the nuclear reactions, increase. When the latter become comparable with the WIMPs luminosity, the standard situation is recovered and the evolutionary track joins the classical
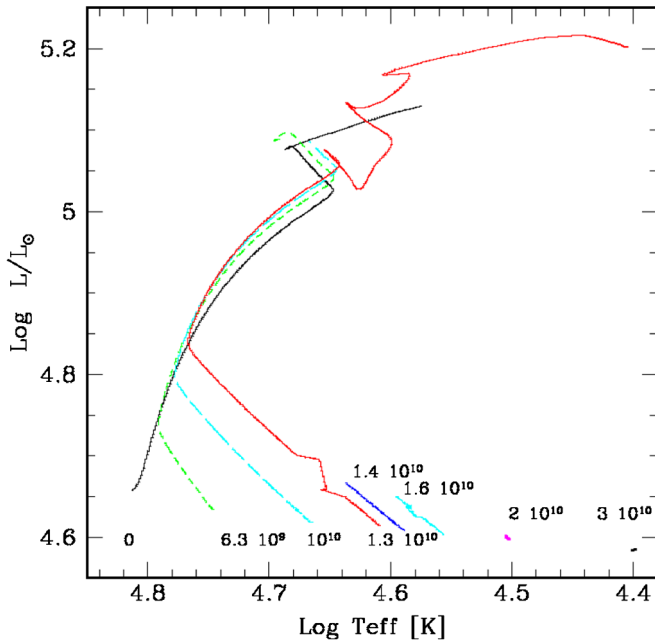
FIG. 1 (color online). Evolutionary tracks of a Pop III $20M_\odot$ star for different WIMP densities (labels in units of GeV cm^{-3}). We have adopted a WIMP model with $m_\chi = 100$ GeV and $\sigma_p^{SD} = 10^{-38}$ cm^2.
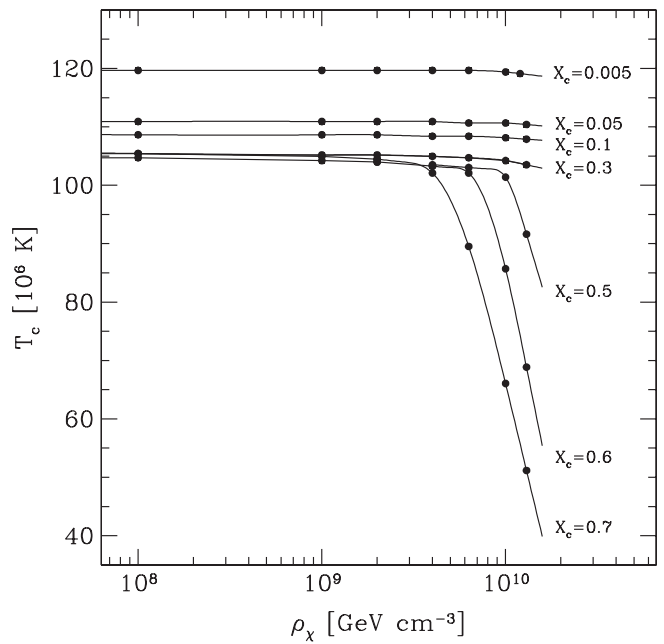

FIG. 2. Temperature of the core as a function of the DM density for the $20M_\odot$ model, at different stages of the core H-burning phase. X_c denotes the mass fraction of hydrogen at the center ($X_c = 0.76$ at the beginning of the core H-burning phase). WIMP parameters as in Fig. 1.

tracks of a star without WIMPs. An important difference from standard evolution is that in the first phase, the nuclear reactions are slowed down and therefore the core H-burning lifetime is prolonged. For dark matter densities $\rho_\chi \lesssim 1.6 \ 10^{10}$ GeV cm^{-3}, the picture is qualitatively the same, and for these models we only show in Fig. 1 the first phases of the evolution. In Fig. 2, we show the core temperature as a function of the DM density, at different stages of the core H-burning phase. At high DM densities hydrogen burns at much lower core temperatures than in the usual scenario, until a certain mass fraction is reached, e.g. $X_c = 0.3$ for $\rho_\chi = 10^{10}$ GeV cm^{-3} and the standard evolutionary track is joined. For increasing DM densities the nuclear reaction rate is more and more delayed until the contraction of the star is inhibited, due to the high DM energy accumulated, and the evolution is frozen. In Fig. 1 for $\rho_\chi = 2 \times 10^{10}$ GeV cm^{-3} and $\rho_\chi = 3 \times 10^{10}$ GeV cm^{-3} the stars seems to remain indefinitely at the ZAMS position. In Fig. 3 we show the core H-burning lifetime as a function of the DM density. In the case of a $20M_\odot$ model, for $\rho \leq 10^9$ GeV cm^{-3} the core H-burning phase is prolonged by less then 10% but the delay increases rapidly for higher DM densities. Extrapolating the curve we determine a critical density, $\rho_c = 2.5 \times 10^{10}$ GeV cm^{-3}, beyond which the core H-burning lifetime is longer than the age of the Universe. All the calculations have been repeated for the $200M_\odot$ model and we find that both the $20M_\odot$ and $200M_\odot$ stars evolutions are stopped for DM densities higher than $5.3 \times 10^{10} \left(\frac{\sigma_p^{SD}}{10^{-38} \text{ cm}^2} \right)^{-1}$ GeV cm^{-3}. We have

also verified that the results weakly depend on the WIMP mass, e.g. the core H-lifetime is modified by a factor 0.2% and 5%, respectively, for $m_\chi = 10$ GeV and $m_\chi = 100$ GeV, if $\rho_\chi = 10^{10}$ GeV cm^{-3}.
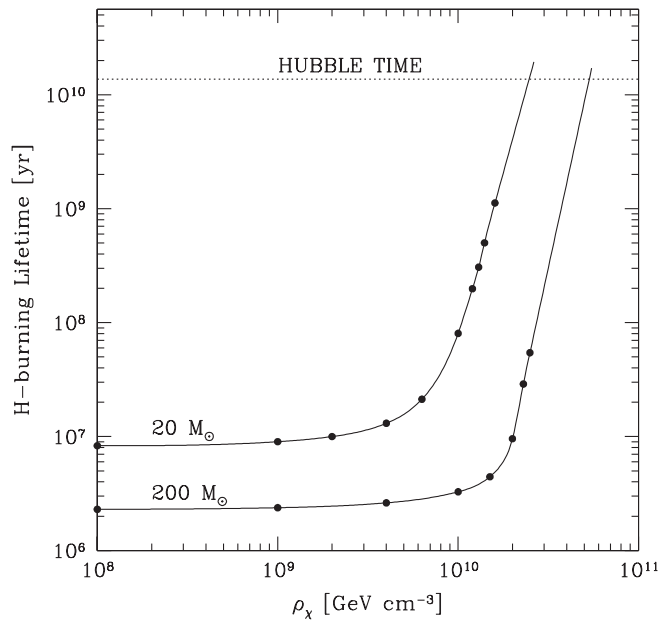

FIG. 3. Variation of the core H-burning lifetime as a function of the WIMP densities for the Pop III 20 and $200M_\odot$ models. WIMP parameters as in Fig. 1.

It is remarkable that under these circumstances, frozen Pop III stars can survive until the present epoch and can be searched for as an anomalous stellar population. In Fig. 4 we show the effective temperature and gravity acceleration at the surface of these frozen Pop III stars, kept in the H-burning phase, for different DM densities. Frozen stars would thus appear much bigger and with much lower surface temperatures with respect to normal stars with the same mass and metallicity. Our results are qualitatively consistent with the preliminary estimates in [11,12] and the analysis in [10]. However, for a given DM density, we obtain a somewhat longer core H-burning lifetime with respect to [10], possibly due to their use of an approximated expression for the capture rate. We have also followed, for selected models, the evolution during the core He-burning phase. During this evolutionary stage, the dark matter luminosity is lower than the nuclear reaction luminosity, therefore the impact of DM annihilations is found to be rather weak. For the $20M_\odot$ model and for $\rho_\chi = 1.6 \times 10^{10}$ GeV cm^{-3} the He-lifetime is prolonged by a factor 1.2, rather than a factor 37 found for the H-burning phase for the same DM density.

In conclusion, we have adapted a stellar evolution code to study the evolution of Pop III stars in the presence of WIMPs. We have shown that provided the DM density remains above a critical value, the annihilation of WIMPs *captured* by Pop III stars can dramatically alter the evolution of these objects and prolong their lifetime beyond the age of the Universe. We have determined the properties of these "frozen" stars and determined the observational properties that may allow to discriminate these objects from ordinary stars.
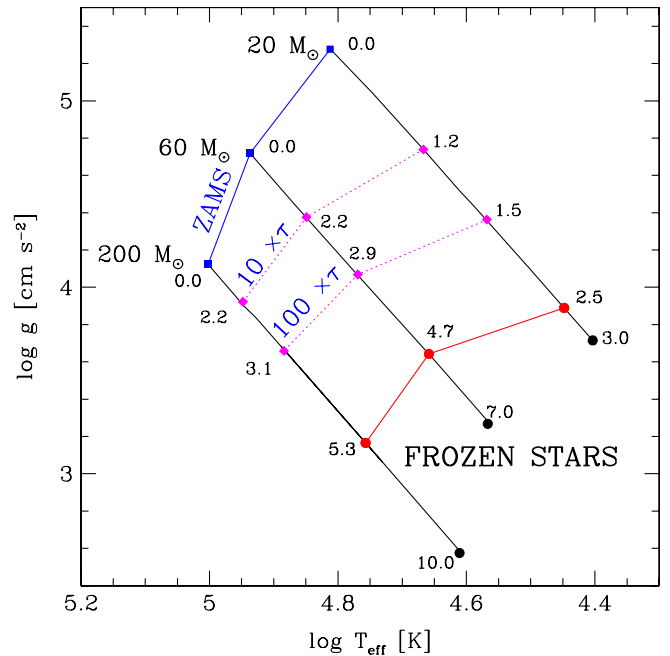
FIG. 4 (color online). ZAMS positions of 20, 60, and $200M_\odot$ Pop III stars in the g vs T_{eff} plane for different DM densities (labels in units of GeV cm^{-3}). Big red (gray) circles correspond to the critical WIMP density (see text). The lines labeled as 10τ and 100τ correspond to models with a lifetime prolonged by 10 and 100 times with respect to the case without WIMPs. WIMP parameters as in Fig. 1.

[1] G. Bertone, D. Hooper, and J. Silk, Phys. Rep. **405**, 279 (2005); L. Bergstrom, Rep. Prog. Phys. **63**, 793 (2000).

[2] G. D. Mack, J. F. Beacom, and G. Bertone, Phys. Rev. D **76**, 043523 (2007).

[3] P. Salati and J. Silk, Astrophys. J. **296**, 679 (1985); A. Renzini, Astron. Astrophys. **171**, 121 (1987); A. Bouquet and P. Salati, Astrophys. J. **346**, 284 (1989); D. Dearborn, G. Raffelt, P. Salati, J. Silk, and A. Bouquet, Astrophys. J. **354**, 568 (1990); P. Salati, G. Raffelt, and D. Dearborn, Astrophys. J. **357**, 566 (1990).

[4] I. V. Moskalenko and L. L. Wai, Astrophys. J. **659**, L29 (2007).

[5] G. Bertone and M. Fairbairn, Phys. Rev. D **77**, 043515 (2008).

[6] M. Fairbairn, P. Scott, and J. Edsjo, Phys. Rev. D **77**, 047301 (2008).

[7] G. Bertone and D. Merritt, Phys. Rev. D **72**, 103502 (2005).

[8] D. Spolyar, K. Freese, and P. Gondolo, Phys. Rev. Lett. **100**, 051101 (2008).

[9] K. Freese, P. Bodenheimer, D. Spolyar, and P. Gondolo, arXiv:0806.0617.

[10] F. Iocco, A. Bressan, E. Ripamonti, R. Schneider, A. Ferrara, and P. Marigo, arXiv:0805.4016.

[11] F. Iocco, Astrophys. J. **677**, L1 (2008).

[12] K. Freese, D. Spolyar, and A. Aguirre, arXiv:0802.1724.

[13] S. Ekström, G. Meynet, A. Maeder, and F. Barblan, Astron. Astrophys. **478**, 467 (2008).

[14] A. Gould, Astrophys. J. **321**, 571 (1987); W. Press and D. N. Spergel, Astrophys. J. **296**, 679 (1985).

[15] Z. Ahmed *et al.* (CDMS Collaboration), arXiv:0802.3530 [Phys. Rev. Lett. (to be published)]; J. Angle *et al.*

(XENON Collaboration), Phys. Rev. Lett. **100**, 021303 (2008).

[16] J. Angle *et al.*, Phys. Rev. Lett. **101**, 091301 (2008); E. Behnke *et al.* (COUPP Collaboration), Science **319**, 933 (2008).

[17] K. Griest and D. Seckel, Nucl. Phys. **283**, 681 (1987).

[18] T. Abel, G. L. Bryan, and M. L. Norman, Science **295**, 93 (2002).

[19] S. Yoon, F. Iocco, and S. Akiyama, arXiv:0806.2662.