A PARTICLE DARK MATTER FOOTPRINT ON THE FIRST GENERATION OF STARS

ILÍDIO LOPES1,2 AND JOSEPH SILK3,4,5

1 Centro Multidisciplinar de Astrofísica, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal; ilidio.lopes@ist.utl.pt
2 Departamento de Física, Escola de Ciência e Tecnologia, Universidade de Évora, Colégio Luís António Verney, 7002-554 Évora, Portugal
3 Institut d’Astrophysique de Paris, F-75014 Paris, France; silk@astro.ox.ac.uk
4 Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA
5 Department of Physics, University of Oxford, Oxford OX1 3RH, UK

Received 2013 October 2; accepted 2014 February 4; published 2014 April 14

ABSTRACT

Dark matter particles with properties identical to those of dark matter candidates hinted at by several international collaborations dedicated to the experimental detection of dark matter (DAMA, COGENT, CRESST; and CDMS-II, although not, most notably, by LUX), which also have a dark matter asymmetry that is identical to the observed baryon asymmetry (Planck and Wilkinson Microwave Anisotropy Probe), may produce a significant impact on the evolution of the first generation of low-metallicity stars. The lifetimes of these stars in different phases of stellar evolution are significantly extended, namely, in the pre-main sequence, main sequence, and red giant phases. In particular, intermediate-mass stars in the red giant phase experience significant changes in their luminosity and chemical composition. The annihilations of dark matter particles affect the interior of the star in such a way that the $3\alpha$ reaction becomes less efficient in the production of carbon and oxygen. This dark matter effect contradicts the excess of carbon and other metals observed today in stars of low mass and low metallicity. Hence, we can impose an upper limit on the dark matter halo density, and therefore on the redshift, at which the first generation of low-metallicity stars formed.

Key words: cosmology: miscellaneous – dark matter – elementary particles – stars: early-type – stars: low-mass

Online-only material: color figures

1. INTRODUCTION

The role of dark matter (DM) in the history of the universe, in particular from 400,000 years up to 1 billion years after the big bang, is well known. As the universe cools down, protons and electrons combine to form neutral atoms of hydrogen and helium. As a result, the universe becomes opaque to most of the radiation and enters into a period known as the dark ages. During this time, DM and baryons form the first gravitationally bound structures (e.g., Tegmark et al. 1997), including the first stars, also called Population III stars (e.g., Barkana & Loeb 2001). Within one billion years after the big bang, these stars light up, most likely re-heating and re-ionizing the intergalactic medium, and the universe becomes dominated by an ionized plasma once again (Abel et al. 2002; Haiman & Loeb 1997). These massive stars collapse, leading to the formation of supernovae and black holes, (Ritter et al. 2012), enriching the interstellar medium with metals and triggering the formation of the first generation of Population II stars with low metallicity (Ritter et al. 2012). Among them are rare, low-mass stars that can possibly be observed today. Although the contribution of the DM to the gravitational field when these first generation stars are formed is relatively well understood, the interaction of DM particles with baryons is not well known, mainly due to the uncertainties in the basic properties of such fundamental particles.

Stars of low mass and low metallicity are among the best known relics of the first generation of stars (Ritter et al. 2012; MacDonald et al. 2013; Bond et al. 2013; Yong et al. 2013), therefore, they can be used to test the impact of annihilating DM from the formation and evolution of such stars. Although low-mass stars form quite rarely, due to their long life span they are among the first stars and are the best candidates to probe Population III. A star with a mass of $0.8 M_\odot$, formed in the early universe, would still shine today, and would be easily recognized by its electromagnetic spectrum, because it would show evidence of hydrogen, helium, and lithium lines, as well as a few very weak metal lines (Caffau et al. 2011; Spite et al. 2013; Caffau et al. 2012). This is a consequence of these stars being formed from material that has a composition very close to that of the universe as it emerged from the big bang.

The experiments dedicated to direct DM searches have been quite successful at restraining the parameter space of DM particles. In particular, by putting strong constraints on the masses of the DM particle candidates, as well as on the scattering cross section of DM particles with baryons. Nevertheless, quite recently, several international collaborations (e.g., DAMA, COGENT, CRESST: Bernabei et al. 2010; Aalseth et al. 2011; Angloher et al. 2012) have reported experimental hints of the existence of a DM particle of low mass, with a mass value in the range of 5–10 GeV. This evidence is reinforced by recent results obtained by the CDMS-II collaboration that suggest the most likely mass of the weakly interacting massive particle (WIMP) is on the order of 8.6 GeV (Agnese et al. 2013). Nevertheless, these results are still controversial, given that other experiments, such as the XENON100 collaboration (Aprile et al. 2012), do not confirm such positive results. Most recently, the LUX collaboration published their first results (Akerib et al. 2013) for DM particles. They provide upper limits at a mass of 33 GeV, and the upper limit on the spin-independent scattering cross section, corresponding to the elastic collision of DM on nuclei, is set at $8 \times 10^{-46}$ cm$^2$.

One of the most exciting challenges in modern cosmology and particle physics is to identify the fundamental nature of DM particles. To discover how DM interacts with baryons (Turck-Chieze & Lopes 2012) and, in particular to explain how it may have contributed to the formation of the first stellar populations.
The impact of DM on stars in the primordial universe (Scott et al. 2011; Spolyar et al. 2009; Natarajan et al. 2009; Freese et al. 2008), and in the local universe (Casanellas & Lopes 2013, 2011b), including the center of our Galaxy, has been addressed by several authors (Casanellas & Lopes 2011a, 2009). In particular, some of these papers have helped to set important constraints on the parameters of symmetric and asymmetric DM. Both the Sun, by means of helioseismology (Lopes & Silk 2010b; Torck-Chieze et al. 2012) and solar neutrinos (Lopes & Silk 2010a, 2012a, 2012b), as well as neutron stars (Kouvaris 2008, 2012; Kouvaris & Tinyakov 2011), are among the most useful stellar objects for constraining the properties of DM.

In this work, we study the impact of light, DM particles in the evolution of low- and intermediate-mass stars. In particular, we choose to focus our study on a class of particles that have properties in common with recent hints of direct detection of DM candidates, but also belong to a theoretical class of DM particles, known as asymmetric $\chi \bar{\chi}$-DM particles (Lopes & Silk 2012a). These particles, like WIMPs, are neutral, cold, massive particles that interact with baryons through a mechanism identical to weak interactions. However, unlike “classical” WIMPs, these can be Dirac particles, i.e., particle ($\chi$) and antiparticle ($\bar{\chi}$) are not the same. This type of $\chi \bar{\chi}$-DM particle, like baryons, also has an asymmetry parameter $\eta_{\chi \bar{\chi}}$ of identical value to the observed value of the baryon asymmetry parameter $\eta_B$.

2. PROPERTIES OF $\chi \bar{\chi}$-DARK MATTER AND BARYONS IN PRIMORDIAL MOLECULAR CLOUDS

Current cosmological observations suggest that the matter in the universe is a mixture of DM particles and baryons. Precise measurements of the DM and baryon matter densities from the Planck mission (Ade et al. 2013) give $\Omega_{DM} h^2 = 0.1161 \pm 0.0028$ and $\Omega_B h^2 = 0.02220 \pm 0.00025$, and from the Wilkinson Microwave Anisotropy Probe (WMAP) mission (Bennett et al. 2013) give $\Omega_{DM} h^2 = 0.1138 \pm 0.0045$ and $\Omega_B h^2 = 0.02264 \pm 0.0005$. Furthermore, the observational baryon asymmetry, $\eta_B$, is also known with relatively good accuracy (Bennett et al. 2013; Ade et al. 2013; Larson et al. 2011; Komatsu et al. 2011). In particular, Bennett et al. (2013) estimate a proxy for $\eta_B$, the baryon/photon ratio, to be of the order of $(6,19 \pm 0.14) \times 10^{-10}$.

In spite of the fact that the origin of DM in the primordial universe is not well known, the nucleosynthesis mechanisms related to the production of light elements is well understood. Recent calculations of standard big bang nucleosynthesis (Coc et al. 2012), including a complete network of more than 400 nuclear reactions, predict an abundance of light elements that are in agreement with WMAP and Planck data, and a negligible production of heavy elements. The ratio of carbon, nitrogen, and oxygen relative to hydrogen is of the order of $10^{-15}$. In particular, the prediction of the abundances of light elements D, $^3$He, $^7$Li, and $^4$He (e.g., Cyburt et al. 2001, 2008; Coc & Angioni 2010) is consistent with the observed values of the baryon relic density and baryon asymmetry. Among the light elements, the helium abundance is the most precisely observed primordial abundance. The current value for the helium mass fraction, $Y_p$, measured by the Planck mission is 0.24770 $\pm$ 0.00012 (Ade et al. 2013). This value is consistent with the helium abundance determined by observations of extragalactic H II regions (e.g., Aver et al. 2010), $Y_p = 0.2566 \pm 0.028$. The difference between the observed values is attributed to the initial enrichment of helium by the first population of massive stars.

Several authors have proposed that the DM observed today was produced in the early universe by a mechanism identical to baryogenesis (e.g., Carena et al. 2009; Dutta & Kumar 2011; Gu et al. 2011). Likewise, during this early phase of the universe, an asymmetry between particles and antiparticles of DM arises, which is similar to the asymmetry between baryons and antibaryons, resulting in a substantial excess of DM today. In this class of cosmological models, the DM is composed of a mixture of particles ($\chi$) and antiparticles ($\bar{\chi}$) of mass $m_{\chi \bar{\chi}}$ (e.g., Iminimiyaz et al. 2011; Drees et al. 2006). In particular, the population of DM particles and antiparticles in the current universe is such that $\Omega_{DM} = \Omega_\chi + \Omega_{\bar{\chi}}$, where $\Omega_\chi$ and $\Omega_{\bar{\chi}}$ are the relic density of DM particles and antiparticles. Among other properties, these particles are also characterized by $g_\gamma$, the number of internal degrees of freedom, and $g_\ast$, the effective number of relativistic degrees of freedom. Furthermore, the asymmetry between DM particles and antiparticles is defined by the asymmetric parameter, $\eta_{\chi \bar{\chi}}$, which is the equivalent of $\eta_B$ for baryons (Lopes & Silk 2012a). We will restrict our study to the case of DM particles with the $\langle \sigma v \rangle_{\chi \bar{\chi}}$-annihilation rate corresponding to the pure s-wave annihilation channel. The case of the p-wave annihilation channel leads to identical results. A detailed discussion can be found in Lopes & Silk (2012a).

In this work, we study the impact of this new DM particle candidate on the evolution of low-metallicity stars with low and intermediate masses. It is worth noticing that the results obtained here are relevant to a large number of DM particle types. Figure 1 shows the present $\Omega_{DM} h^2$ of several cosmological models of DM particles with a mass of 10 GeV and different values of $\eta_{\chi \bar{\chi}}$ and $\langle \sigma v \rangle_{\chi \bar{\chi}}$. As shown, only a small set of models have a value of $\Omega_{DM} h^2$ that is consistent with present day observations. We also indicate other sets of models corresponding to particles with a mass of 100 GeV and 1000 GeV, which are also compatible with the observed value of $\Omega_{DM} h^2$. Table 1 presents the numerical values for a few of these sets of models. These results show that for models with very low values of $\eta_{\chi \bar{\chi}}$, there...
3. EVOLUTION OF STARS IN LOW-METALLICITY ENVIRONMENT IN THE EARLY UNIVERSE

Current models of primordial stellar formation suggest that the first generation of stars formed in DM mini-halos at a redshift of \( z \sim 20–70 \), as part of binary or higher-order multiple stellar systems (Turk et al. 2009; Clark et al. 2011; Greif et al. 2011). The very first of these stars would have formed at \( z \sim 65 \). They are expected to be massive or very massive stars with \( M \sim 10–100 M_\odot \) (Naoz et al. 2006; Fialkov et al. 2012; Visbal et al. 2012). Numerical simulations at high-resolution on small scales suggest that these stars formed within high density DM halos with a total mass of \( 10^9 M_\odot \) (Abel et al. 2002; Bromm et al. 1999). These massive stars have a very short lifetime, of just a few million years, and their very rapid evolution terminates as a collapsing black hole or an exploding supernova, enriching the interstellar medium with metals, at least in the later case. Just afterward, a second generation of stars forms within these molecular clouds, which are believed to be the birth place of the low-mass, low-metallicity stars observed today.

In the following, we will study the impact that \( \chi \bar{\chi} \)-DM will have on the evolution of these stars, which are considered to be formed in primordial molecular clouds with a large amount of DM. The baryons will be mainly hydrogen and helium with a very small amount of heavy elements. We choose the initial abundance of helium to be \( Y_p = 0.25 \) and the metallicity to be \( Z = 10^{-5} \). We noticed that the difference of 3.5% between the two observational determinations of \( Y_p \) (discussed in the previous section) has a minor impact on the evolution of such low-metallicity stars. The relative abundance of particles and antiparticles in the molecular cloud is proportional to the relic density of particles and antiparticles in the local universe (see Figure 1 and Table 1).

The capture of DM from the hosting halo by a star proceeds by two mechanisms: adiabatic contraction, a process by which protostars form in the center of dense DM halos, generating a local enhancement of the DM density in the core of the star caused by the increasing gravitational influence of the gas collapsed at the center of the halo (Spolyar et al. 2008), and the gravitational accretion of DM by the star (throughout its lifetime) from the hosting halo (Lopes et al. 2002; Casanellas & Lopes 2009; Scott et al. 2009), which is the leading process discussed in this paper.

Therefore, the amount of DM captured by the star depends explicitly, among other quantities, on the local density of DM where the star is formed \( \rho_{DM} \), the mass of the DM particle \( m_{DM} \), the annihilation rate \( \langle \sigma v \rangle_{DM} \), and the scattering cross section of DM with baryons. This cross section describes the collision of the DM particles with hydrogen and heavier elements, usually referred to as the spin-dependent or spin-independent scattering cross section, \( \sigma_{SD} \) and \( \sigma_{SI} \) (Lopes & Silk 2012a). It follows that the total number of particles, \( N\chi \), and antiparticles, \( N\bar{\chi} \), that accumulate inside the star at a certain epoch is computed by numerically solving the system of coupled equations:

\[
\frac{dN_i}{dt} = C_i - C_a N\chi N\bar{\chi} - C_e N_i,
\]

with \( i \) being \( \chi \) or \( \bar{\chi} \). The constant \( C_i \) gives the rate of the capture of particles (antiparticles) from the DM halo, \( C_a \) gives the annihilation rate of particles with antiparticles, and \( C_e \) gives the evaporation rate of DM particles from the star (Griest & Seckel 1987). Nevertheless, as we restrict our analysis to particles with a mass larger than 7 GeV, the evaporation rate is negligible.

Table 1: \( \chi \bar{\chi} \)-dark Matter Particles

| \( m_{DM} \) (GeV) | \( n_{DM} \) \( \times 10^{10} \) | \( \langle \sigma v \rangle_{DM} \) \( \times 10^{-24} \text{ cm}^3 \text{ s}^{-1} \) | \( \Omega_{\chi} h^2 \) (%) | \( \Omega_{\bar{\chi}} h^2 \) (%) |
|-------------------|-------------------|-------------------|-------------------|-------------------|
| 10                | 0.0001            | 1.6              | 50                | 50                |
| 10\(^*\)           | 0.050             | 1.5              | 55                | 45                |
| 10                | 0.155             | 1.6              | 63                | 37                |
| 10                | 0.141             | 1.7              | 68                | 32                |
| 10                | 0.399             | 8                | 100               | 0                 |
| 100***             | 0.0001            | 1.6              | 50                | 50                |
| 100**              | 0.0100            | 1.5              | 55                | 45                |
| 100                | 0.0185            | 1.6              | 64                | 36                |
| 100                | 0.0224            | 1.8              | 78                | 22                |
| 100                | 0.0407            | 9                | 100               | 0                 |
| 1000               | 0.0001            | 1.7              | 50                | 50                |
| 1000               | 0.0008            | 1.9              | 60                | 40                |
| 1000               | 0.0013            | 1.9              | 67                | 33                |

Notes.

\(^*\) The \( \eta \) footnote on \( m_{DM} \) indicates the DM particles for which their impact on the evolution of a few stars was computed (see Figure 2).

\(^\dagger\) This value is of the same order of magnitude as the \( \eta \) value of \( n_{DM} \) (WMAP and Planck observations), depends strongly on the mass of the DM particle. In the cases shown, these correspond to the values \( 7 \times 10^{-11}, 7 \times 10^{-12}, \) and \( 7 \times 10^{-11} \) for cosmological models containing particles with masses of 100, 10, and 10 GeV, respectively. In fact, it is interesting to note that \( \chi \bar{\chi} \) models with \( m_{DM} = 10 \text{ GeV} \) and high \( \eta_{DM} \) (strongly asymmetric DM particles) are the ones for which the \( \eta_{DM} \) is closer to the observational value of \( \eta \) (see Table 1).

Unfortunately, there are no reliable constraints on the annihilation rate \( \langle \sigma v \rangle_{DM} \). Although, it is not directly comparable to this study, it is worth mentioning that, by using Milky Way satellite galaxies, the Fermi Collaboration (Ackermann et al. 2014) have put a constraint on the thermal-averaged annihilation rate so that it is less than \( 3 \times 10^{-28} \text{ cm}^3 \text{ s}^{-1} \), for \( m_{DM} \leq 10 \text{ GeV} \) in the \( bb \) channel, and for \( m_{DM} \leq 15 \text{ GeV} \) in the \( bb \) and \( \tau \bar{\tau} \) channels. It is interesting to note that this annihilation rate value, \( \langle \sigma v \rangle_{DM} \), is two orders of magnitude below that of the DM model discussed in this work.

We emphasize that the DM model with \( m_{DM} = 100^{**} \text{ GeV} \) corresponds to symmetric (Majorana) DM particles for which \( \Omega_{\chi} = \Omega_{\bar{\chi}} \equiv 50\% \) (see Table 1). However, unlike in classical DM models, in this case the DM presents a certain degree of asymmetry, \( \eta_{DM} \), which can vary between \( 10^{-14} \) and \( 10^{-11} \), a few orders of magnitude smaller than the observed value of \( \eta \). Finally, we note that symmetric DM, as found in most of the literature, corresponds to a very low value of \( \eta_{DM} \) and a very high annihilation rate, \( \langle \sigma v \rangle_{DM} \). Similarly, asymmetric DM corresponds to a very high \( \eta_{DM} \) and very low annihilation rate, \( \langle \sigma v \rangle_{DM} \). In the following sections, we study the impact of a set of a few candidate DM particles on stellar evolution, for which \( \Omega_{DM} \) is consistent with the current observations (see Figure 1).
The coefficient, \( f_{\text{DM}} \) the DM particles are shown in Table 1. The results obtained are consistent with previous estimations done for the case of \( n_\text{and} \) \( \rho_\text{accreted by the star} \) (Zentner 2009). The capture rate of particles (antiparticles) by the star at each step of evolution is computed numerically from the expression obtained by Gould (1987) as implemented by Gondolo et al. (2004). The description of how this capture process is implemented in our code is discussed in Lopes et al. (2011).

Following the capture of DM by the star, its evolution is affected by two DM-related physical mechanisms, a new energy transport mechanism that removes energy from the core of the star and an extra source of energy resulting from DM annihilations. In DM halos of high density, the latter mechanism always outperforms that of DM energy transport, making any effects of the latter process negligible. Nevertheless, both physical mechanisms are included in our numerical computations.

The annihilation of DM particles occurring inside the star injects several particle species into the stellar plasma, among others, energetic photons \( \gamma' \), s, electron/positron pairs \( e^\pm \), neutrinos \( \nu' \), muons \( \mu^\pm \), pions \( \pi' \), nucleons and antinucleons, \( N' \) and \( N' \), and gauge bosons \( Z' \) and \( W'^\pm \). The unstable particles, such as \( \pi' \), \( \mu^\pm \), \( Z' \), and \( W'^\pm \) will rapidly decay into more stable particles. We assume that most of these particles, except for neutrinos, interact either by electromagnetic or nuclear strong forces with the local baryons, as they have very short mean free paths. These particles rapidly reach thermal equilibrium with the rest of the plasma. Overall, these \( \chi\bar{\chi} \)-annihilation channels provide the stellar core with an additional source of energy. The energy generation rate \( \epsilon_{\text{DM}} \) due to \( \chi\bar{\chi} \)-DM pair annihilation is given by

\[
\epsilon_{\text{DM}}(r) = f_{\text{DM}} n_\chi n_{\bar{\chi}} \rho^{-1}(\sigma v)_{\text{DM}}
\]

in units of energy per mass per time (erg g\(^{-1}\) s\(^{-1}\)), where \( n_\chi \) and \( n_{\bar{\chi}} \) are the density number distribution of \( \chi \) and \( \bar{\chi} \) DM particles, and \( \rho \) is the radial profile of density inside the star. The coefficient, \( f_{\text{DM}} \), corresponds to the fraction of annihilation channels that are absorbed by the stellar plasma, which we set equal to 2/3. The remaining 1/3 corresponds to energy lost in the form of neutrinos. Actually, more precise particle physics models suggest that the energy loss is of the order of 10% (Scott et al. 2009).

In agreement with hints from present day direct DM search measurements (e.g., DAMA, COGENT, CRESST, CDMS-II; Bernabei et al. 2010; Aalseth et al. 2011; Angloher et al. 2012; Agnese et al. 2013), the fiducial DM particle in our simulations has a mass of 10 GeV, the scattering cross section of baryons is such that \( \sigma_{\text{SD}} = 10^{-41} \) cm\(^2\) and \( \sigma_{\text{SI}} = 10^{-41} \) cm\(^2\). A detailed account of the sensitivity of the evolution of the star to \( \sigma_{\text{SD}} \) and \( \sigma_{\text{SI}} \) can be found in Lopes et al. (2011). The values of \( \eta_{\text{DM}} \) and \( (\sigma v)_{\text{DM}} \) were chosen in agreement with the current observation of \( \Omega_{\text{DM}}h^2 \). We have also computed stellar models for DM particles with a mass of 100 GeV. Other properties of the DM particles are shown in Table 1. The results obtained are consistent with previous estimations done for the case of symmetric DM models (Casannellas & Lopes 2009; Freese et al. 2008; Scott et al. 2009; Fairbairn et al. 2008).

In this work, we numerically compute for the first time the impact of DM particles and antiparticles for different values \( \eta_{\text{DM}} \) and \( (\sigma v)_{\text{DM}} \) (see system of Equation (1) and Table 1). Figure 2 shows the Hertzsprung–Russell (H–R) diagram of several stars (0.6–5 \( M_\odot \)) evolving within different \( \chi\bar{\chi} \)-DM halos. The presence of DM in the stellar cores visibly affects the evolution of the star (notably, luminosity, radius, and temperature) at different phases of its evolution. The density of the DM halo, the relative proportion of DM particles and antiparticles and the DM annihilation rate are the most important factors affecting the evolution of the star. If the star forms in a dense DM halo, constituted by DM with identical proportions of particles and antiparticles (i.e., \( \eta_{\text{DM}} \) is small) and a large annihilation rate, the extra source of energy provided by DM annihilations, \( \epsilon_{\text{DM}} \), becomes competitive with other sources of energy (see Figure 3). Otherwise, the energy produced by DM annihilations is negligible.

These results show that stars formed in molecular clouds with this type of asymmetric DM have a modified evolution path in the H–R diagram. This is valid for low-mass stars, as pointed out previously for the case of symmetric DM (Scott et al. 2009; Casannellas & Lopes 2009; Freese et al. 2008; Spolyar et al. 2008), but, as shown here, it is also very important for intermediate-mass stars. In general, more massive stars require a large amount of DM to affect their luminosity (see Figure 3). We found that for low-mass stars (with \( M = 0.6 \ M_\odot \)) the luminosity changes for DM halos with \( \rho_{\text{DM}} \geq 10^7 \) GeV cm\(^{-3}\) and for intermediate mass (with mass \( M = 2–5 \ M_\odot \)). This effect is observed when \( \rho_{\text{DM}} \geq 10^8 \) GeV cm\(^{-3}\).

In general, the total luminosity of the low- and intermediate-mass stars is affected in a different way in the various phases of their evolution. As shown in Figure 1, the luminosity of a low-mass star is reduced during the pre-main, main sequence, and red giant phases (stars with 0.6–0.7 \( M_\odot \) blue lines). However,
the luminosity of an intermediate-mass star is reduced during the pre-main and main sequence phases (stars with $3–4 \, M_\odot$ cyan lines), but increases during the red giant phase (stars with $2–5 \, M_\odot$ red and green lines). In the case of intermediate-mass stars in the red giant phase, the luminosity changes by a factor of several orders of magnitude (stars with $2 \, M_\odot$ and $5 \, M_\odot$ red and green lines). This could present a very interesting target for future observational surveys.

In certain stellar evolution scenarios, the $\epsilon_{DM}$ almost balances the gravitational contraction of the star. Stars in the pre-main sequence phase evolve very slowly toward the main sequence, and stars in the main sequence and the red giant phase follow a similar evolution pattern. As a consequence the life of low- and intermediate-mass stars is largely extended. In an extreme case scenario, the star could stay in the same phase of evolution infinitely long (see Figure 4). Typical examples are stars with a mass of $3 \, M_\odot$ and $1.0 \, M_\odot$, in the first case, the star could extend its life in the red giant phase by a factor of three due to its slow evolution during this phase (see Figure 4, star with $M = 3.0$ red line), and in the second case, the star could live longer than the present age of the universe (see Figure 4, star with $M = 1.0$ yellow line).

The diminution of the evolution time step due to the presence of DM inside a star affects its chemical composition. This process is particularly relevant during the red giant phase of an intermediate-mass star.

In a classical scenario of evolution (without DM), as the star departs from the main sequence (when the hydrogen burning has finished), the star experiences a gravitational contraction of its internal layers and an expansion of its external layers, which leads to a significant increase of its core temperature and surface luminosity. These temperature increases trigger $\alpha$ nuclear reactions that, in turn, lead to the production of $^{12}\text{C}$ and $^{16}\text{O}$ in the stellar core. In the case of stars formed within an enriched DM environment, the evolution is identical to the previous case but with a difference. The gravitational contraction during the red giant phase is slowed down, leading to a much longer phase. The ignition of $3\alpha$ nuclear reactions and subsequent production of $^{12}\text{C}$ is retarded. Figure 5 shows the production of $\text{H}$, $^4\text{He}$, and $^{12}\text{C}$ and the central temperature during the red giant phase of stars with mass $2–5 \, M_\odot$. For example, in the case of a star with a mass of $4 \, M_\odot$ that has a red giant phase with a time span of 10 Myr, if the star forms in a DM halo the time span is 100 Myr (see Figure 5). Therefore, the production of chemical elements like $^{12}\text{C}$ proceeds at a lower rate. This effect is contrary to the chemical anomalies observed in the first generation of stars. Abundance anomalies have been observed in up to a third of extremely low metallicity stars (Yong et al. 2013). The C-enhanced stars are also O-rich (Na, Mg, and Al are enhanced) and the conventional explanation appeals to the mass accretion following supernovae explosion after nucleosynthesis and the selective fall-back of zero heavy element massive stars (Norris et al. 2013).
consistent with Figure 2.

stellar evolution phases. The most obvious impact of asymmetric luminosity, chemical composition, and lifetimes in the different stellar evolution phases, namely, the pre-main sequence, main sequence, and red giant phases. Furthermore, stars formed in dense DM halos will be at an earlier stage of evolution than stars formed in less dense halos. Equally, a larger amount of DM is necessary to affect the evolution of more massive stars. In particular, we found that for intermediate-mass stars evolving in relatively mild DM halos, unlike low-mass stars, their luminosity decreases at the end of the main sequence phase, and increases at the beginning of the red giant phase (see Figure 2).

One of the most interesting consequences that we have found is related to the change in the chemical composition of intermediate-mass stars during the red giant phase. The annihilation of DM significantly increases the lifetime of the star in the red giant phase, reducing the time step of the temperature increase and consequently reducing the efficiency of $\alpha$-nuclear to produce $^{12}$C and $^{16}$O. Contrary to this evolution scenario is the fact that some of the low-mass stars known to be among the oldest stars in the universe present an excess of chemical elements such as carbon and oxygen, despite their very small metallicity. Therefore, this provides a constraint on the density of the DM host halos.

The possible discovery of primordial stars of intermediate mass and low metallicity is theoretically possible as DM can extend the lifetimes of these stars, which would constitute a strong indication of the influence of DM on the formation of these first generations of stars. Otherwise, the proof of non-existence of such stars provides a strong constraint on the properties of the hypothesized DM particles.

The work of I.L. was supported by grants from “Fundaçao para a Ciência e Tecnologia” and “Fundaçao Calouste Gulbenkian.” The research of J.S. has been supported at IAP by the ERC project 267117 (DARK) hosted by Université Pierre et Marie Curie-Paris 6 and at JHU by NSF grant OIA-1124403. We are grateful to the authors of the DarkSUSY and CESAM codes for having made their codes publicly available.

## REFERENCES

Aalseth, C. E., Barbeau, P. S., Bowden, N. S., et al. 2011, PhRvL, 106, 131301

Abe, T., Bryan, G. L., & Norman, M. L. 2002, Sci, 295, 93

Ackermann, M., Albert, A., Anderson, B., et al. 2014, PhRvD, 89, 042001

Ade, P. A. R., Aghanim, N., Armitage-Caplan, C., et al. 2013, arXiv:1303.5076

Agne, R., Ahmed, Z., Anderson, A. J., et al. 2013, PhRvL, 111, 1301

Akerib, D. S., Araujo, H. M., Bai, X., et al. 2013, PhRvL, in press (arXiv:1310.8214)

Angloher, G., Bauer, M., Bavykina, I., et al. 2012, EPJC, 72, 1971

Apirle, E., Alfonsi, M., Arisaka, K., et al. 2012, PhRvL, 109, 181301

Aver, E., Olive, K. A., & Skillman, E. D. 2010, JCAP, 05, 003

Barkana, R., & Loeb, A. 2001, PhR, 349, 125

Bennett, C. L., Larson, D., Weiland, J. L., et al. 2013, ApJS, 208, 20

Bernabei, R., Belli, P., Cappella, F., et al. 2010, EPJC, 67, 39

Bond, H. E., Nelson, E. P., VandenBerg, D. A., Schaefer, G. H., & Harmer, D. 2013, ApJL, 765, L12

Bromm, V., Coppi, P. S., & Larson, R. B. 1999, ApJL, 527, L5

Caffau, E., Bonifacio, P., Francois, P., et al. 2011, Natur, 477, 67

Caffau, E., Bonifacio, P., Francois, P., et al. 2012, A&A, 542, 51

Carenna, M., Nardi, G., Quiro, M., & Wagner, C. E. M. 2009, NuPhB, 812, 243

Casanelas, J., & Lopes, I. 2009, ApJL, 705, 135

Casanelas, J., & Lopes, I. 2011a, ApJL, 733, L51

Casanelas, J., & Lopes, I. 2011b, MnRAS, 410, 535

Casanelas, J., & Lopes, I. 2013, ApJL, 765, L23

Clark, P. C., Glover, S. C. O., Klessen, R. S., & Bromm, V. 2011, ApJ, 727, 110

Coc, A., Goriely, S., Xu, Y., Saimpert, M., & Vangioni, E. 2012, ApJ, 744, 158

Coc, A., & Vangioni, E. 2010, JPCS, 202, 2001

The Astrophysical Journal, 786:25 (7pp), 2014 May 1

Therefore, these observational constraints set an upper limit to the density of the DM halo where these stars formed. For example, low-metallicity stars with a mass smaller than 1 $M_\odot$, cannot form in DM halos with a density larger than $10^7$ GeV cm$^{-3}$, otherwise, contrary to observation, these stars will be deficient in metals.

## 4. CONCLUSIONS

We have studied the impact of light asymmetric DM particles in the evolution of the first generation of low- and intermediate-mass stars formed in a low-metallicity environment. We found that the most suitable candidate is a DM particle with a mass of 10–100 GeV with a DM asymmetry close to the baryon asymmetry. Depending on the specific DM properties of the molecular cloud where these stars are formed, this type of DM could have a major impact on their evolution, by changing their luminosity, chemical composition, and lifetimes in the different stellar evolution phases. The most obvious impact of asymmetric DM in the evolution of a star is the extension of their lifetimes resulting from slower evolution through the different stellar phases.
