DARK MATTER CAPTURE AND ANNIHILATION ON THE FIRST STARS: PRELIMINARY ESTIMATES

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ABSTRACT

Assuming that dark matter is dominated by WIMPs, it accretes by gravitational attraction and scattering over baryonic material and annihilates inside celestial objects, giving rise to a “dark luminosity” which may potentially affect the evolution of stars. We estimate the dark luminosity achieved by different kinds of stars in a halo with DM properties characteristic of the ones where the first star formation episode occurs. We find that both massive, metal-free and small, galactic-like stars can achieve dark luminosities comparable to or exceeding those due to their nuclear burning. This might have dramatic effects over the evolution of the very first stars, known as Population III.

Subject headings: dark matter — early universe — stars: early-type — stars: evolution

1. INTRODUCTION

Observations continue to provide evidence for a dark component of matter in the universe, whose motivations and possible candidates are thoroughly reviewed by Bertone et al. (2005). It was realized quite early that scattering between dark matter (DM) and baryons would result in capture of DM particles on celestial bodies, with the most remarkable effect of stars hosting within their bosom an additional source of energy due to the captured DM annihilation. Since then, several authors have studied the possibility of exploiting the effects of an additional, potentially inexhaustible energy source within stars in order to constrain DM properties; among the most recent, Moskalenko & Wai (2007) and Bertone & Fairbairn (2008) study compact objects, and Fairbairn et al. (2008) and Scott et al. (2007) have performed preliminary numerical calculations of the stellar evolution. All the results seem to converge over the fact that within a neutralino-dominated DM scenario, and with an astrophysical environment with typical galactic DM velocity profiles of the order of $v \approx 10^2$ km s$^{-1}$, DM densities required in order to have appreciable effects on stellar evolution are $\rho_s \geq 10^3$ GeV cm$^{-3}$, achievable only within the central two parsecs of our Galaxy, with similar restrictions holding for other types of galaxies: DM burning would not affect most of the stars in our local universe. However, so far no one has studied the effects of DM burning on the first stars in the universe: according to the current ΛCDM cosmological description the early universe is quite a peculiar place for stellar formation to take place. The almost total absence of metals (Iocco et al. 2007), the small mass and angular momentum of the young and dense halos where the first stars form, and the lack of strong magnetic fields all intertwine, giving the Population III stars peculiar properties; above all is to be mentioned the characteristic formation of a single, massive (30–300 $M_\odot$) star (Abel et al. 2002; Gao et al. 2007). Massive, metal-free stars would evolve quickly through the main-sequence (MS), burning all of their fuel within timescales of 10$^7$ years and proceeding quickly through the following element burning, until at the oxygen-burning stage the temperature and entropy are so high that copious $e^+e^-$ production takes place, pressure drops, and a runaway collapse is triggered. This leads to explosive nucleosynthesis which results in direct collapse to a black hole, or to a direct dramatic explosion, or to stellar pulsations followed by a final violent explosion (Heger & Woosley 2002). An “alteration” of the basic stellar formation scenario has been pointed out by Spolyar et al. (2008): at times much earlier than the actual formation of a protostar ($T \leq 10^4$ K, $n \leq 10^{10}$ cm$^{-3}$) DM embedded in the halo annihilates at a rate such that the energy deposited exceeds that lost by the molecular cooling of the gas. Although these semianalytical results have to be confirmed by more detailed numerical simulations, it is clear that this process could change the history of primordial stellar formation by preventing the cloud from collapsing, or by slowing it down or else inducing fragmentation of the baryonic cloud. Although this process is different from the one we study it is clearly related to it: when the cloud becomes opaque enough to efficiently scatter WIMPs off baryons, another energy source would be added in the center, as opposed to the pure DM annihilation, which is diffuse everywhere in the halo. Here we present preliminary estimates of the DM accretion and annihilation inside a star, as it would result if it had formed in a “classical” way, without any effect from the DM annihilation at lower densities and temperatures.

2. DARK MATTER CAPTURE AND ANNIHILATION IN STARS

Models of DM capture and annihilation on celestial bodies were developed in the 1980s by many authors, and here we collect the results of most concern for this Letter. At the equilibrium between capture and annihilation the event rate is (Gould 1987)

$$C = 4\pi \int_0^{\infty} dr r^2 \frac{dC(r)}{dV},$$

where

$$\frac{dC(r)}{dV} = \left(\frac{6}{\pi}\right)^{1/2} \sigma v \frac{\rho_s}{m_s} \rho \frac{v^2(r)}{2\eta A^2} \left[\frac{1}{2} A_+ A_- - \frac{1}{2} \left|\chi(-\eta, \eta) - \chi(A_+, A_-)\right| \right]$$

$$+ \frac{1}{2} A_+ e^{-x^2} - \frac{1}{2} A_- e^{-x^2} - \eta e^{-x^2},$$

L1
The DM density and its velocity dispersion play a fundamental role in determining the accretion rate on any stellar object; in the local universe, high DM densities are achieved only in the very center of galaxies; in particular, in the Milky Way a cuspy profile is believed to have formed by accretion around a central black hole, over the long lifetime of our Galaxy and its central object, as shown for instance in Bertone & Merritt (2005) and references therein. DM particles adopt Keplerian velocities around the central object, thus reaching their highest velocities where the DM density peaks; on the other hand, most of the stellar mass is not located in the center of the Galaxy, but in regions where the DM density is too small to consistently affect stellar evolution.

In a primordial environment the scenario is quite different: in a young halo such as the ones where Population III stars form, average densities are quite high, as the concentration of DM, $c$, is higher in a younger universe. Moreover, no central object exists yet so DM particles do not have time to develop a Keplerian velocity profile: the star itself is believed to be the very first object to form in the center of the halo (where the DM density is highest). In a primordial halo, for the whole lifetime of a Population III star, we can assume DM dispersion velocities to be a Maxwell-Boltzmann distribution around the central value corresponding to the virial temperature of the halo itself. In order to extrapolate the values of the DM density $\rho_\chi$ at the location of a primordial star, we quote state-of-the-art simulations of the collapse of the first object. They achieve impressive resolutions, having to be stopped at central gas (baryon) densities of $O(10^{25}$ particles cm$^{-3}$), achieved at a radius of $\approx 10^5$ cm (M. J. Turk 2007, private communication); unfortunately this is not (yet) enough to resolve the actual star; simulations stop following DM particles even earlier, when the density is homogenous within a radius of $\approx 10^{19}$ cm, thus not allowing us to have more detailed insights on smaller scales. For a central region of radius $10^{15}$ cm one finds an enclosed mass $M_{\text{tot}} \approx 10^6 M_\odot$, corresponding to a $\rho_\chi \approx 10^{-12}$ GeV cm$^{-3}$; this data, quoted from the state-of-the-art simulations (M. J. Turk 2007, private communication; Turk 2008) is in agreement with the results extrapolated from previous simulations and also with the ones obtained by much simpler semi-analytical models of adiabatically contracted DM halos, as in Spolyar et al. (2008). Namely, the halo followed in Turk’s cosmological simulations has $M_{\text{tot}} = O(10^6 M_\odot)$, a virial temperature $T \approx 10^5$ K, and therefore a virial velocity $\tilde{v} \approx 10^3$ cm s$^{-1}$, according to mass-temperature relation evolution with redshift in Levine et al. (2002) and references therein. It is likely that the final $\rho_\chi$ in the center of the halo will be higher at the time of stellar formation; moreover, the effects triggered by a process such as the one discussed in Spolyar et al. (2008) are not trivial to predict. Here we limit ourselves to present results using $\rho_\chi = 10^{26}$ GeV cm$^{-3}$ as our fiducial value, adopting $\langle av \rangle = 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ (Bertone et al. 2005) and $\sigma_v = 10^{-24}$ (10$^{-23}$) cm$^2$ for the spin-dependent (spin-independent) case (Akerib et al. 2006; Desai et al. 2004); this corresponds to a fiducial value for our parameter $D = 10^{-32}$ (10$^{-37}$) GeV s cm$^{-2}$ for the spin-dependent (spin-independent) case. Results for different values can be easily rescaled.

Using the equations introduced in § 2, we have estimated those quantities for WIMPs captured by a 75 $M_\odot$ extremely metal-poor ($Z = 10^{-4} Z_\odot$) star, described in Woosley et al. (2002); our results do not change within the order of magnitude if we adopt the values of a metal-free, $100 M_\odot$ star described in Marigo et al. (2001). In fact, stellar radii of $O(R, \approx 10 R_\odot)$ during the MS and $R, \approx 100 R_\odot$ during the helium-burning phases are achieved both by the 75 $M_\odot$ star in Woosley et al. (2002) and the metal-free $100 M_\odot$ one in Marigo et al. (2001), as can be seen from a detailed table in the first case and extrapolated from the diagram on page 5 in the second. Unfortunately, the fundamental paper describing the properties, dynamics, and details of massive, metal-free stars in the pair-instability supernovae (PISNe) range, Heger & Woosley (2002), lacks detailed information about the MS, focusing on the post-hydrogen-burning phase onward; however, we are confident that within the order of magnitude confidence represented
by this estimate, our values are indicative of the whole stellar mass range. In the case of the 75 $M_\odot$ star, in order to estimate the mass of the core for the stages following the H burning, and therefore the central mass of the star which has a definitely different composition, we use the approximate relation from Heger & Woosley (2002) (which has to be taken with care in this case, as we are out of the PISNe range) $M_{\text{He}} = (13/24) \times (M_{\text{AMS}} - 20)$, thus obtaining a helium core for the 75 $M_\odot$ star of $M_{\text{He}} \approx 30 M_\odot$. During the helium-burning stage the star’s central density is $\rho_{\text{He}} \approx 3 \times 10^9$ g cm$^{-3}$. Approximating the core with a constant density of $\rho_{\text{He}} = 10^7$ g cm$^{-3}$ one gets a central He core of radius $R_{\text{He}} \approx 5 \times 10^8$ cm ($O(R_{\odot})$). The remaining 45 $M_\odot$ of hydrogen will continue accreting DM (with a spin-independent cross section, while the helium core will continue accreting it with a spin-dependent one). In Table 1 we report the quantities introduced in § 2 for the 75 $M_\odot$ hydrogen star, as described so far, for a neutralino with mass $m_\chi = 100$ GeV.

The luminosity of a 75 $M_\odot$ star is of the order of $10^8 L_\odot \approx 10^{39}$ ergs s$^{-1}$ throughout all its life, until the oxygen-burning stage, as for instance in Marigo et al. (2001). Our estimates show that a dark luminosity $10^{37}$ ergs s$^{-1} \leq L_\chi \leq 10^{38}$ ergs s$^{-1}$ is achieved for DM densities in the range [$10^9$ GeV cm$^{-3}$, $10^{15}$ GeV cm$^{-3}$]. These values are extremely interesting, as they are comparable (actually exceed, at the cross section upper limit) the stellar luminosity during the main sequence.

Transport effects: an upper limit can be obtained by using equation (5); the highest temperature WIMPs can achieve correspondence to the escape velocity where most of the WIMPs are concentrated, namely within the radius $r_c$. By setting the WIMP temperature with the escape velocity at $r_c$, and number densities $n_\chi$ and $n_p$ for WIMPs and protons, respectively, one gets values of $\epsilon_\chi$ as reported in Tables 1 and 2. The DM transport effects in the core seem to be negligible for the whole neutralino density and mass range studied: the stellar luminosity $L_\star = 10^{39}$ ergs s$^{-1}$ needs an efficiency $\epsilon_\star \approx 10^4$ ergs s$^{-1}$ cm$^{-3}$, if one assumes a nuclear core of $10^{10}$ cm, 2 orders of magnitude more than upper limit value of $\epsilon_\chi$ achieved with the highest DM density considered in our range. During the helium burning, $\tau_c$ is to be read in a very indicative way: the higher DM density accumulated during the MS may simply consume itself until it reaches a lower concentration at the equilibrium in each part of the star. However, we find it interesting that a capture rate equivalent to the helium core is achieved by the huge hydrogen envelope surrounding it.

In Table 2 we show results for low-mass stars; although the formation of low-mass stars within the Population III it is not the currently favored hypothesis, state of the art simulations cannot totally rule out a low-mass peak in the IMF. Some authors, as for instance Choudhury & Ferrara (2006), do actually invoke a low-mass, Salpeter-like Population III.

These values are very interesting, too: as already mentioned, other authors have already studied the evolutionary behavior of low-mass stars in presence of a DM annihilation source, and more detailed calculations are expected to be available soon. We only stress that for low-mass stars the behavior of metal-free objects is not so dramatically different as for massive stars, and that results obtained for metal-rich, “usual” stars can be used at least for a first-approximation understanding of the behavior of low-mass Population III stars in presence of a relevant dark luminosity.

4. DISCUSSION

Without entering detailed calculations, we wish to focus attention on several issues that could be raised by an “unorthodox” behavior of massive Population III stars, hoping this Letter will be used as a starting point for more detailed and extensive analysis. The formation of primordial stars has to be carefully investigated in the presence of DM annihilation, according to the preliminary, interesting results obtained by Spolyar et al. (2008); if slowed down, the cloud might start capturing DM at an early stage, and dark luminosity might start playing a role even before the formation of the actual star, if the cloud collapse is not stopped by this process. Assuming that a primordial star forms in a “standard” fashion, and lately develops dark luminosities of the order of our upper limits, there is no telling, without actual simulations and detailed calculations, what the behavior of the object could be (we recall that for the 75 $M_\odot$ star our fiducial value for $D = 10^{-32}$ GeV s cm$^{-2}$ is $L_\chi = 10^{39}$ ergs s$^{-1}$, 1 order of magnitude greater than the stellar luminosity). In the likely case that the actual value of $\sigma_0$ is not its quoted upper limit, some interesting scenarios can still be envisioned: Population III stars are thought to explode as PISNe, due to the high entropy and temperature of the core at the time of oxygen burning; what if a dark luminosity comparable to the stellar one can reduce both entropy and temperature of the star, thus leading it through the oxygen-burning phases without dramatic instabilities? What would be the effects of an $L_\chi$ only comparable with the required stellar luminosity over the short $pp$ phase at the beginning of the hydrogen burning forced by the lack of CNO elements, given the very slow $pp$ energy production sensitivity from temperature? At the same time, stellar evolution in the presence of an additional energy source might lead to very different nucleosynthetic yields; the odd-Z element deficiency has been long considered one of the “signatures” of Population III stars; what if different temperatures (plus an additional electron source due to neutralino decay) would result in a different peculiar signature? What would happen to a star which is sup-

### Table 1

| $A_\chi$ | $L_\chi$ (ergs s$^{-1}$) | $\tau_c$ (s) | $r_c$ (cm) | $n_\chi^2$ (GeV cm$^{-3}$) | $\epsilon_\chi$ (ergs s$^{-1}$ cm$^{-3}$) |
|---------|----------------|-------------|----------|----------------|----------------|
| 1 ...... | $10^{39}$ | $10^7$ | $10^{10}$ | $10^{37}$ | $10^7$ |
| 4 ...... | $10^{39}$ | $10^7$ | $10^{10}$ | $10^{37}$ | $10^2$ |
| 1 ...... | $10^{39}$ | $10^7$ | $10^{10}$ | $10^{37}$ | 1 |

Notes.—Values for a 75 $M_\odot$, initial metallicity $Z = 10^{-4}$ star, in a neutralino case with $m_\chi = 100$ GeV. $D = 10^{-32}$ (10$^{-35}$) GeV s cm$^{-2}$ for the spin-dependent (spin-independent) case.

### Table 2

| $M_\odot$ ($M_\odot$) | $L_\chi$ (ergs s$^{-1}$) | $\tau_c$ (s) | $r_c$ (cm) | $n_\chi^2$ (GeV cm$^{-3}$) | $\epsilon_\chi$ (ergs s$^{-1}$ cm$^{-3}$) |
|----------------|----------------|-------------|----------|----------------|----------------|
| 1 ...... | $10^{39}$ | $10^7$ | $10^{10}$ | $10^{37}$ | $10^7$ |
| 13 ...... | $10^{39}$ | $10^7$ | $10^{10}$ | $10^{37}$ | $10^2$ |
| 25 ...... | $10^{39}$ | $10^7$ | $10^{10}$ | $10^{37}$ | $10^2$ |

Notes.—Values for main-sequence, low-mass stars, initial metallicity $Z = 10^{-4}$, in a neutralino case with $m_\chi = 100$ GeV. $D = 10^{-32}$ (10$^{-35}$) GeV s cm$^{-2}$ for the spin-dependent (spin-independent) case.
ported mainly by DM burning, and would survive long enough to follow its host halo in a merger, until DM environmental conditions change? Population III stars are thought to be the first engine for the reionization of the universe, as they are a huge source of ionizing photons as a consequence of their very high surface temperature; can dark luminosity modify it, and thus result in a modification of the reionization models?

It is straightforward to ask whether a clear signature of this process could be recognized. High-energy neutrinos produced by DM annihilation inside the Sun are expected to be observed in the future by IceCube (Mena et al. 2007); the same process would lead to a diffuse high-energy neutrino background from the first stars. However, a massive star burning DM for $\tau \approx 10^4$ years with $L_\odot = 10^{40}$ ergs s$^{-1}$ would release a total energy $E_\odot \approx 10^{51}$ ergs; let us take as an upper limit that all of this energy ends up in neutrinos (the only annihilation channel being $\chi \chi \to \nu \nu$), adopt the formalism described in Iocco et al. (2008) and the same stellar formation rate (the “fiducial” one as in Choudhury & Ferrara 2005), and assume the formation of a single stellar object per halo. One gets a flux at the Earth, at the peak energy $E_\odot = m_\chi (1 + \bar{z}) \leq 10$ GeV ($m_\chi = 100$ GeV) of $\Phi \leq 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ ($\bar{z} \geq 10$ being the “central” redshift of the Population III episode); this flux is buried several orders of magnitude below the diffuse atmospheric neutrino background at the same energy as from Evoli et al. (2007), thus making neutrinos a nonefficient tool for studying this process.

5. PRELIMINARY CONCLUSIONS

Within a WIMP-dominated DM scenario, with structure formation taking place in a “standard” scenario, primordial stars accrete DM much more efficiently than most of modern, galactic stars, mainly due to the peculiar conditions of the halos where they form. Within a large region of the relevant parameter space (DM velocity dispersion, density, and WIMP-baryon scattering cross section), the energy deposited inside the star by the accreted DM annihilation is comparable to (and even exceeds) the stellar, nuclear luminosity. This raises several questions about the real nature of primordial stars, and about whether their behavior as stellar objects is dictated by baryons only.

Whereas describing the effects of DM “burning” on the first stars would, at this stage, be pure speculation, we aim with this Letter to stimulate discussion and interest on this topic, and qualitatively propose scenarios whose validity will have to be checked in the future. However, we think the questions raised by our preliminary estimates are extremely relevant for our understanding of first-object formation and evolution in the universe, which is becoming a much more complicated puzzle than previously expected.

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REFERENCES

Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Akerib, D. S., et al. (CDMS Collaboration). 2006, Phys. Rev. Lett., 96, 011302
Bertone, G., & Fairbairn, M. 2008, Phys. Rev. D, 77, 043515
Bertone, G., Hooper, D., & Silk, J. 2005, Phys. Rep., 405, 279
Bertone, G., & Merritt, D. 2005, Phys. Rev. D, 72, 103502
Choudhury, T. R., & Ferrara, A. 2005, MNRAS, 361, 577
———. 2006, MNRAS, 371, L55
Desai, S., et al. (Super-Kamiokande Collaboration). 2004, Phys. Rev. D, 70, 083523
Evoli, C., Grasso, D., & Maccione, L. 2007, J. Cosmol. Astropart. Phys., 06, 003
Fairbairn, M., Scott, P., & Edsjö, J. 2008, Phys. Rev. D, 77, 047301
Gao, L., Abel, T., Frenk, C. S., Jenkins, A., Springel, V., & Yoshida, N. 2007, MNRAS, 378, 449
Gould, A. 1987, ApJ, 321, 571
Grüest, K., & Seckel, D. 1987, Nucl. Phys. B, 283, 681
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Iocco, F., Mangano, G., Miele, G., Pisanti, O., & Serpico, P. D. 2007, Phys. Rev. D, 75, 087304
Iocco, F., Murase, K., Nagataki, S., & Serpico, P. D. 2008, ApJ, 675, 937
Levine, E. S., Schulz, A. E., & White, M. J. 2002, ApJ, 577, 569
Marigo, P., Girardi, L., Chiosi, C., & Wood, P. R. 2001, A&A, 371, 152
Mena, O., Palomares-Ruiz, S., & Pascoli, S. 2007, preprint (arXiv:0706.3909)
Moskalenko, I. V., & Wai, L. L. 2007, ApJ, 659, L29
Scott, P., Edsjö, J., & Fairbairn, M. 2007, preprint (arXiv:0711.0991)
Spolyar, D., Freese, K., & Gondolo, P. 2008, Phys. Rev. Lett., 100, 051101
Turk, M. J. 2008, in AIP Conf. Proc., First Stars III, ed. B. W. O’Shea (New York: AIP), in press
Woosley, S. E., Heger, A., & Weaver, T. A. 2002, Rev. Mod. Phys., 74, 1015