Dark stars: a new study of the first stars in the Universe

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Abstract. We have proposed that the first phase of stellar evolution in the history of the Universe may be dark stars (DSs), powered by dark matter (DM) heating rather than by nuclear fusion. Weakly interacting massive particles, which may be their own antipartners, collect inside the first stars and annihilate to produce a heat source that can power the stars. A new stellar phase results, a DS, powered by DM annihilation as long as there is DM fuel, with lifetimes from millions to billions of years. We find that the first stars are very bright ($\sim 10^6 L_\odot$) and cool ($T_{\mathrm{surf}} < 10\,000\,\mathrm{K}$) during the DS phase, and grow to be very massive (500–1000 times as massive as the Sun). These results differ markedly from the standard picture in the absence of DM heating, in which the maximum mass is smaller and the temperatures are much hotter ($T_{\mathrm{surf}} > 50\,000\,\mathrm{K}$); hence DS should be observationally distinct from standard Pop III stars. Once the DM fuel is exhausted, the DS becomes a heavy main sequence star; these stars eventually collapse to form massive black holes that may provide seeds for supermassive black holes observed at early times as well as explanations for recent ARCADE data and for intermediate black holes.

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Contents

1. Introduction

We have proposed [1] (hereafter Paper I) a new phase of stellar evolution: the first stars to form in the Universe may be dark stars (DSs), powered by dark matter (DM) heating rather than by fusion. Here DM, while constituting a negligible fraction of the star's mass, provides the energy source that powers the star. The first stars in the Universe mark the end of the cosmic dark ages, provide the enriched gas required for later stellar generations, contribute to reionization and may be precursors to black holes that coalesce and power bright early quasars. One of the outstanding problems in astrophysics is to investigate the mass and properties of these first stars. Our results differ in important ways from the standard picture of first stars without DM heating.

Weakly interacting massive particles (WIMPs) are the best motivated DM candidates. WIMP annihilation in the early Universe provides the right abundance today to explain the DM content of our Universe. This same annihilation process will take place at later epochs in the Universe wherever the DM density is sufficiently high to provide rapid annihilation. The first stars to form in the Universe are a natural place to look for significant amounts of DM annihilation, because they form at the right place and the right time. They form at high redshifts, when the Universe was still substantially denser than it is today, and at the high-density centers of DM haloes.

The first stars form inside DM haloes of $10^6 M_\odot$ (for reviews, see e.g. [2]–[5]; see also [6]–[8]). One star is thought to form inside one such DM halo. The first stars may play an important role in reionization, in seeding supermassive black holes, and in beginning the process of production of heavy elements in later generations of stars.

It was our idea to ask, what is the effect of the DM on these first stars? We studied the behavior of WIMPs in the first stars, and found that they can radically alter the stellar evolution. The annihilation products of the DM inside the star can be trapped and deposit enough energy to heat the star and prevent it from further collapse. A new stellar phase results, a DS, powered by DM annihilation as long as there is DM fuel, for millions to billions of years.

1.1. Weakly interacting DM

WIMPs are natural DM candidates from particle physics. These particles, if present in thermal abundances in the early Universe, annihilate with one another so that a predictable number of them remain today. The relic density of these particles is

$$\Omega_\chi h^2 = (3 \times 10^{-27} \, \text{cm}^3 \, \text{s}^{-1})/\langle \sigma v \rangle_{\text{ann}}, \tag{1}$$

where the annihilation cross section $\langle \sigma v \rangle_{\text{ann}}$ of weak interaction strength automatically gives the right answer, near the WMAP [9] value $\sim 23\%$. This coincidence is known as 'the WIMP miracle' and is the reason why WIMPs are taken so seriously as DM candidates. The best WIMP candidate is motivated by supersymmetry (SUSY): the lightest neutralino in the Minimal Supersymmetric Standard Model (see the reviews by [10]–[13]).

This same annihilation process is also the basis for DM indirect detection searches. The first paper discussing annihilation in stars was [14]; the first papers suggesting searches for annihilation products of WIMPs in the Sun were by Silk and co-workers [15]; and in the Earth by Freese [16] as well as Krauss *et al* [17]. Other studies of WIMPs in today's stars (less powerful than in the first stars) include [18]–[23]. This paper reviews the study of WIMP annihilation as a heat source for the first stars.

As our canonical parameter values, we take $m_\chi = 100 \, \text{GeV}$ for the WIMP mass and $\langle \sigma v \rangle_{\text{ann}} = 3 \times 10^{-26} \, \text{cm}^3 \, \text{s}^{-1}$ for the annihilation cross section but consider a variety of masses and cross sections.

2. Three criteria for DM heating

WIMP annihilation produces energy at a rate per unit volume

$$Q_{\text{ann}} = \langle \sigma v \rangle_{\text{ann}} \rho_\chi^2 / m_\chi, \tag{2}$$

where ρ_χ is the DM energy density inside the star and n_{h} is the stellar hydrogen density. Here and throughout, we have set the speed of light $c = 1$. Paper I [1] outlined the three key ingredients for DSs: (i) high DM densities, (ii) the annihilation products get stuck inside the star and (iii) DM heating wins over other cooling or heating mechanisms. These same ingredients are required throughout the evolution of the DSs, whether during the protostellar phase or during the main sequence phase.

First criterion: high DM density inside the star. One can see from equation (2) that the DM annihilation rate scales as WIMP density squared, because two WIMPs must find each other to annihilate. Thus the annihilation is significant wherever the density is high enough. DM annihilation is a powerful energy source in these first stars (and not in today's stars) because the DM density is high. Firstly, DM densities in the early Universe were higher by $(1 + z)^3$. Secondly, the first stars form exactly in the centers of DM haloes where the densities are high (as opposed to today's stars that are scattered throughout the disk of the galaxy rather than at the Galactic Center). We assume for our standard case that the DM density inside the $10^6 M_\odot$ DM halo initially has an NFW (Navarro, Frenk and White [24]) profile for both DM and gas, with substantial DM in the center of the halo (we note that we obtain qualitatively the same result for cored haloes [28]). Thirdly, a further DM enhancement takes place in the center of the halo: as the protostar forms, it deepens the potential well at the center and pulls in more DM as well. We have computed this enhancement in several ways [1] as discussed in the next paragraph.

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Fourthly, the original DS is only $\sim 1 M_\odot$; then it accretes more baryons as well as more DM up to almost $1000 M_\odot$, in the process increasing the DM density inside the star. Fifthly, at later stages, we also consider possible further enhancement due to capture of DM into the star (discussed below).

Enhanced DM density due to adiabatic contraction: Paper I recognized a key effect that increases the DM density: adiabatic contraction. As the gas falls into the star, the DM is gravitationally pulled along with it. Given the initial NFW profile, we follow its response to the changing baryonic gravitational potential as the gas condenses. Paper I used a simple Blumenthal method [25], which assumes circular particle orbits to obtain estimates of the density. Our original DM profile matched that which was obtained numerically in [6] with $\rho_\chi \propto r^{-1.9}$, for both their earliest and latest profiles; see also [26] for a discussion. Subsequently we performed an exact calculation [28] using the Young method [27], which includes radial orbits, and confirmed our original results (within a factor of two). Thus we feel confident that we may use the simple Blumenthal method in our work. We found

$$\rho_\chi \sim 5 (\mathrm{GeV\,cm^{-3}})(n_\mathrm{h}\,\mathrm{cm^3})^{0.81}, \tag{3}$$

where n_h is the gas density. For example, due to this contraction, at a hydrogen density of $10^{13}\,\mathrm{cm^{-3}}$, the DM density is $10^{11}\,\mathrm{GeV\,cm^{-3}}$. Consequently, in the protostellar phase equation (2) becomes

$$Q_\mathrm{ann} \simeq 10^{-29}\,\mathrm{erg\,s\,cm^{-3}}\;\frac{\langle \sigma v \rangle}{(3 \times 10^{-26}\,\mathrm{cm^3\,s^{-1}})}\left(n_\mathrm{h}\,\mathrm{cm^3}\right)^{1.6}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right). \tag{4}$$

In the case of a cored profile (studied in [28]), the DM densities in the star at a given hydrogen density are lower; yet they are still high enough for DM annihilation to be important. The only difference is that the star must contract to a somewhat higher gas density in order for the DM heating to become important. The resultant object is not substantially different. Without adiabatic contraction, DM heating in the first stars would be so small as to be irrelevant.

Second criterion: DM annihilation products get stuck inside the star. In the early stages of Pop III star formation, when the gas density is low, most of the annihilation energy is radiated away [29]. However, as the gas collapses and its density increases, a substantial fraction f_Q of the annihilation energy is deposited into the gas, heating it up at a rate $f_Q Q_\mathrm{ann}$ per unit volume. While neutrinos escape from the cloud without depositing an appreciable amount of energy, electrons and photons can transmit energy to the core. We have computed estimates of this fraction f_Q as the core becomes more dense. Once $n \sim 10^{11}\,\mathrm{cm^{-3}}$ (for $100\,\mathrm{GeV}$ WIMPs), e^- and photons are trapped and we can take $f_Q \sim 2/3$.

Third criterion: DM heating is the dominant heating/cooling mechanism in the star. We find that, for WIMP mass $m_\chi = 100\,\mathrm{GeV}$ ($1\,\mathrm{GeV}$), a crucial transition takes place when the gas density reaches $n > 10^{13}\,\mathrm{cm^{-3}}$ ($n > 10^9\,\mathrm{cm^{-3}}$). Above this density, DM heating dominates over all relevant cooling mechanisms, the most important being H_2 cooling [30].

Figure 1 shows evolutionary tracks of the protostar in the temperature-density phase plane with DM heating included (Yoshida *et al* [31]), for two DM particle masses (10 and $100\,\mathrm{GeV}$). Moving to the right on this plot is equivalent to moving forward in time. Once the black dots are reached, DM heating dominates over cooling inside the star, and the DS phase begins. The protostellar core is prevented from cooling and collapsing further. The size of the core at this point is $\sim 17\,\mathrm{AU}$ and its mass is $\sim 0.6 M_\odot$ for $100\,\mathrm{GeV}$ mass WIMPs. A new type of object is created, a DS supported by DM annihilation rather than fusion.
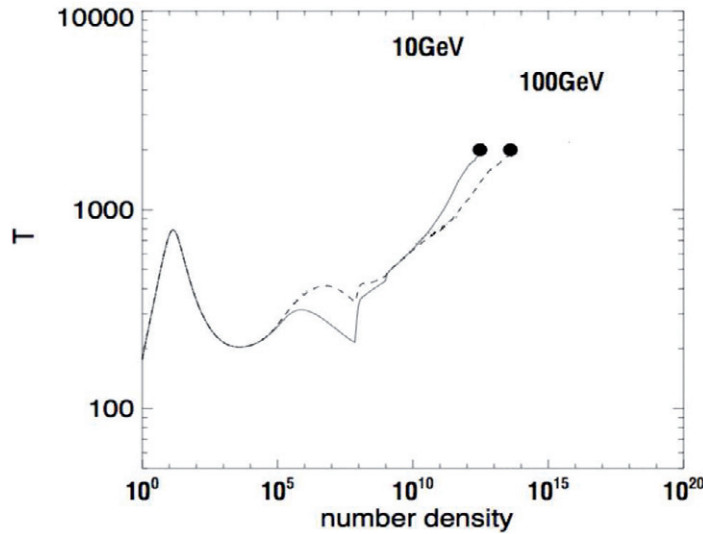
Figure 1. Temperature (in degrees K) as a function of hydrogen density (in cm^{-3}) for the first protostars, with DM annihilation included, for two different DM particle masses (10 and 100 GeV). Moving to the right in the figure corresponds to moving forward in time. Once the 'dots' are reached, DM annihilation wins over H_2 cooling, and a DS is created.

3. Building up the mass

This point is the beginning of the life of the DS, a DM-powered star that lasts until the DM fuel runs out. We have found the stellar structure of the DSs (hereafter DS) [35]. After forming with the properties described in the previous paragraph, the DS accrete mass from the surrounding medium. In our paper we build up the DS mass as it grows from $\sim 1 M_\odot$ to $\sim 1000 M_\odot$. As further gas accretes onto the DS, more DM is pulled along with it into the star. At each step in the accretion process, we compute the resultant DM profile in the DS by using the Blumenthal prescription for adiabatic contraction. The DM density profile is calculated at each iteration of the stellar structure, so that the DM luminosity can be determined.

We allow surrounding matter from the original baryonic core to accrete onto the DS, with three different assumptions for the mass accretion: (i) $3 \times 10^{-3} M_\odot$ yr^{-1}, (ii) the variable rate from Tan and McKee [36] and (iii) the variable rate from O'Shea and Norman [37]. The Tan/McKee rate decreases from $1.5 \times 10^{-2} M_\odot$ yr^{-1} at a DS mass of $3 M_\odot$ to $1.5 \times 10^{-3} M_\odot$ yr^{-1} at $1000 M_\odot$. The O'Shea/Norman rate decreases from $3 \times 10^{-2} M_\odot$ yr^{-1} at a DS mass of $3 M_\odot$ to $3.3 \times 10^{-4} M_\odot$ yr^{-1} at $1000 M_\odot$. As the mass increases, the DS radius adjusts until the DM heating matches its radiated luminosity. We find polytropic solutions for DSs in hydrostatic and thermal equilibrium. We build up the DS by accreting $1 M_\odot$ at a time, always finding equilibrium solutions. We find that initially the DS are in convective equilibrium, from 100 to 400 $M_\odot$ there is a transition to radiative and heavier DS are radiative. As the DS grows, it pulls in more DM, which then annihilates. We continue this process until the DM fuel runs out at $M_{DS} \sim 800 M_\odot$ (for 100 GeV WIMPs).

We have performed a complete study of building up the DS mass and finding the stellar structure at each step in mass accretion. In addition to the heating due to DM annihilation, we included additional heat sources due to gravitational potential energy and fusion in the later stages of accretion, as the DM begins to run out and the star contracts and heats up.
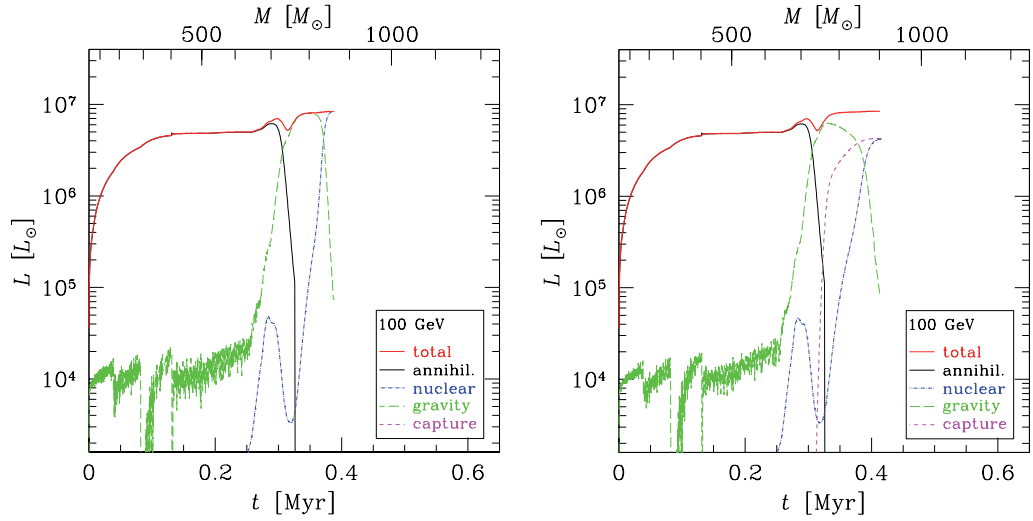
Figure 2. Luminosity evolution for the 100 GeV case as a function of time (lower scale) and stellar mass (upper scale). The solid (red) top curve is the total luminosity. The lower curves give the partial contributions of different sources of energy powering the star (a) (upper frame) without capture, and (b) (lower frame) with 'minimal' capture. In both frames, the total luminosity is initially dominated by DM annihilation (the total and annihilation curves are indistinguishable until about 0.3 Myr after the beginning of the simulation); then gravity dominates, followed by nuclear fusion. In the lower frame, capture becomes important at late times.

Thus the energy supply for the star changes with time and comes from four major sources:

$$L_{\text{tot}} = L_{\text{DM}} + L_{\text{grav}} + L_{\text{nuc}} + L_{\text{cap}}, \tag{5}$$

where the ingredients are the DM luminosity L_{DM}, gravitational contraction L_{grav} (as the DM begins to run out), fusion luminosity L_{nuc} (once the star has contracted enough to reach high temperatures for fusion), and the contribution L_{cap} to the luminosity due to captured DM (discussed below). The general thermal equilibrium condition is then that the stellar luminosity L_* matches the heat supply,

$$L_* = L_{\text{tot}}. \tag{6}$$

Figure 2 shows the different contributions to the luminosity as a function of time for the 100 GeV case using the Tan/McKee accretion rate. We include feedback mechanisms that can prevent further accretion. Once the stellar surface becomes hot enough (we take 50 000 K), when the DM is running out, the mechanisms studied by McKee/Tan [36] can prevent accretion (albeit at a higher stellar mass than in the standard case they considered).

Figure 3 shows the stellar structure for the case of constant accretion rate and assuming a convective star ($n = 1.5$); more accurate results will be found in our upcoming paper. One can see 'the power of darkness': although the DM constitutes a tiny fraction ($< 10^{-3}$) of the mass of the DS, it can power the star. The reason is that WIMP annihilation is a very efficient power source: 2/3 of the initial energy of the WIMPs is converted into useful energy for the star, whereas only 1% of baryonic rest mass energy is useful to a star via fusion.
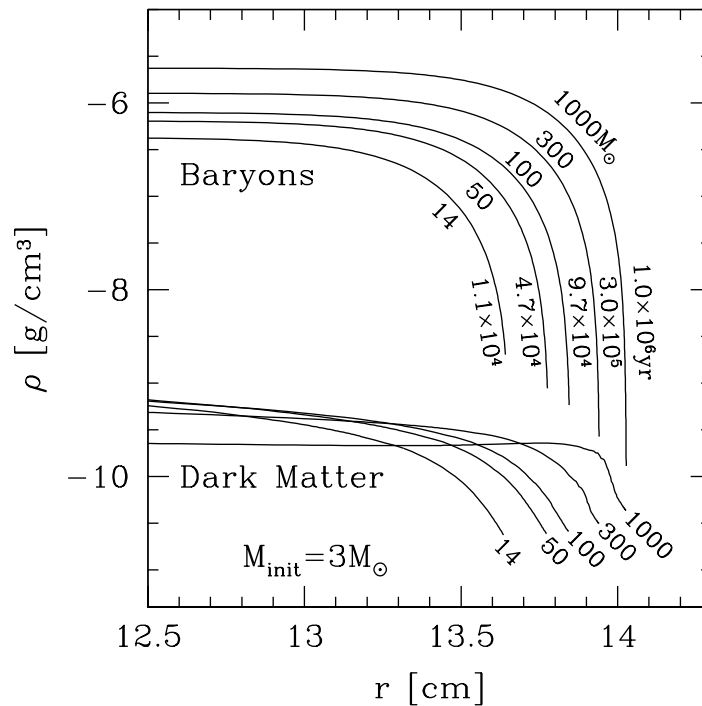
Figure 3. Evolution of a DS ($n = 1.5$) as mass is accreted onto the initial protostellar core of $3M_\odot$; this figure assumes a constant accretion rate $\dot{M} = 3 \times 10^{-3} M_\odot \, \text{yr}^{-1}$. The set of upper (lower) curves correspond to the baryonic (DM) density profile at different masses and times. Note that DM constitutes $< 10^{-3}$ of the mass of the DS.

4. Later stages: capture

The DSs will last as long as the DM fuel inside them persists. The original DM inside the stars runs out in about a million years. However, as discussed in the next paragraph, the DM may be replenished by capture, so that the DS can live indefinitely due to DS annihilation. Capture only becomes important once the DS is already large (hundreds of solar masses), and only with the additional particle physics ingredient of a significant WIMP/nucleon elastic scattering cross section at or near the current experimental bounds.

The new source of DM in the first stars is capture of DM particles from the ambient medium. Any DM particle that passes through the DS has some probability of interacting with a nucleus in the star and being captured. The new particle physics ingredient required here is a significant scattering cross section between the WIMPs and nuclei. Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a somewhat free parameter, set only by bounds from direct detection experiments. Two simultaneous papers [40, 41] found the same basic idea: the DM luminosity from captured WIMPs can be larger than fusion for the DS. Two uncertainties exist here: the scattering cross section and the amount of DM in the ambient medium to capture from. DS studies following the original papers that include capture have assumed (i) the maximal scattering cross sections allowed by experimental bounds and (ii) ambient DM densities that are never depleted. With these assumptions, DS evolution models with DM heating after the onset of fusion have now been studied in several

papers [42]–[44]. The two original papers on capture in Pop III stars, as well as these additional papers, would all apply to later generations of stars (versus the very first ones), as the stellar masses on the zero age main sequence (ZAMS) were taken to be $\sim 100 M_\odot$.

We suspect that the DS will eventually leave their high-density homes in the centers of DM haloes, especially once mergers of haloes with other objects takes place, and then the DM fuel will run out. The star will eventually be powered by fusion.

In our work, we have considered two separate cases: (i) 'no capture': the case where ambient density and/or scattering cross section are simply not high enough for capture to matter and (ii) 'minimal capture': the case where the stellar luminosity (on the ZAMS) has equal contributions from DM heating and from fusion.

If the capture rate were much higher, say two or more orders of magnitude higher than the minimal value considered here, the star could stay DM powered and sufficiently cool such that baryons can in principle continue to accrete onto the star indefinitely, or at least until the star is disrupted. This latter case will be explored in a future paper where it will be shown that the DS could easily end up with a mass on the order of several tens of thousands of solar masses and a lifetime of least tens of millions of years.

We also briefly mention a separate work [51], in which we studied a different possible DM candidate: we studied the effect of primordial black holes on the first stars. We found that these small black holes, again adiabatically contracted into the first stars, fall to the center of the star by dynamical friction. There they form a single large black hole that can eat the entire star and accrete from the surrounding medium. Again we have a mechanism for forming $> 1000 M_\odot$ black holes at early times, which may explain or serve as seeds for the intermediate mass or large black holes found in many places in the Universe.

5. DSs in light of PAMELA data

Recently, observations by PAMELA [32], the Fermi Gamma Ray Space Telescope [33] and other cosmic ray experiments have generated a great deal of interest in DM particles that annihilate at a high rate to leptons. An excess of positrons has been seen which (one may speculate) could be explained in terms of DM annihilation. However, such an explanation requires nonstandard WIMP properties. In particular, the annihilation rate must be supplemented by a large boost factor ~ 10–10^4. Such a boost factor could plausibly arise due to particle physics such as a Sommerfeld enhancement [34]. Regardless of the origin of the boost, the effect on DSs would be to multiply the right-hand side of equation (4) by the boost factor. Then DM heating would win against molecular hydrogen cooling more easily, at a smaller value of the gas density. In essence, the 'dots' in figure 1 would be reached a point farther to the left in the plot. This is equivalent to keeping the boost factor at a value $B = 1$ but reducing the WIMP mass, since the heating rate scales as B/m_χ. Thus the case of $m_\chi = 1\,\text{TeV}$ and $B = 1000$ is exactly the same as the case of $m_\chi = 1\,\text{GeV}$ and $B = 1$. We have not yet studied one of the most interesting cases for PAMELA, $m_\chi = 600\,\text{GeV}$ and $B = 1000$ but plan to do so. As B increases, the DM annihilation kicks in early, the DM annihilates away more quickly and the resultant stellar mass will be somewhat lower. To explain the PAMELA excess without overproducing antiprotons, the annihilation is primarily to leptons. This difference will affect our results only by factors O(1). Any annihilation products (including electrons and positrons) other than neutrinos get trapped by the DS and heat it up. Hence DM designed to explain the PAMELA data will quantitatively, but not qualitatively, change our results.

6. Results and predictions

While DM powers the DSs, they are cool (surface temperatures less than $10\,000$ K) and bright ($10^6 L_\odot$). These properties are very different from standard Pop III stars, which have surface temperatures exceeding $30\,000$ K. One can thus hope to find DS and differentiate them from standard Pop III stars, e.g. in JWST.

Once the DM fuel runs out inside the DS, the star contracts until it reaches 10^8 K and fusion sets in. Our final result [35] in all cases is very large first stars; e.g. for 100 GeV WIMPs, the first stars have $M_{\rm DS} = 800 M_\odot$. The implication is that main-sequence stars of Pop III are very massive. Regardless of uncertain parameters such as the DM particle mass, the accretion rate, and scattering, DS are cool, massive, puffy and extended. The final masses lie in the range $500–1000 M_\odot$, very weakly dependent on particle masses, which were taken to vary over a factor of 10^4.

One may ask how long the DSs live. If there is no capture, they live until the DM they are able to pull in via adiabatic contraction runs out; the numerical results show lifetimes in the range 3×10^5–5×10^5 year. If there is capture, the DM fuel is replenished. Hence DSs can continue to exist as long as they reside in a medium with a high enough density of DM to provide their entire energy by scattering, capture and annihilation. Hence DSs can last from millions to billions of years, without and with capture, respectively.

Once the stars are on the main sequence, powered by fusion, they will not last very long before collapsing to form black holes. DS would make plausible precursors of the $10^9 M_\odot$ black holes observed at $z = 6$ [39, 45], of intermediate mass black holes, of black holes at the centers of galaxies and of the black holes recently inferred as an explanation of the extragalactic radio excess seen by the ARCADE experiment [48]. However, see [45]–[47] who present caveats regarding the growth of early black holes. The final fate of our stars once they reach the MS is uncertain; it is possible that they could become supernovae [49], leaving behind perhaps half their mass as black holes. In this case the presumed very bright supernova could possibly be observable, and the resultant black holes could still be important. In addition, the black hole remnants from DS could play a role in high-redshift gamma ray bursts thought to take place due to accretion onto early black holes (we thank G Kanbach for making us aware of this possibility).

Standard Pop III stars are thought to be $\sim(100–200) M_\odot$ (though some papers consider masses up to $600 M_\odot$, whereas DS lead to far more massive MS stars). Heger and Woosley [38] showed that for $140 M_\odot < M < 260 M_\odot$, pair instability supernovae lead to odd–even effects in the nuclei produced; such element abundances have not been observed. Other constraints on DS will arise from cosmological considerations. A first study of their effects (and those of the resultant MS stars) on reionization have been done by Schleicher *et al* [50], and further work in this direction is warranted.

7. Conclusion

95% of the mass in galaxies and clusters of galaxies is in the form of an unknown type of DM. One of the key properties of WIMP candidates is its annihilation cross section, yielding the proper relic density today. As a consequence of this annihilation, the first stars in the Universe may provide another avenue to test the DM hypothesis. These stars may be powered by DM annihilation, and one can look for them in upcoming telescopes. It is an exciting prospect to discover a new type of star powered by the DM in the Universe.

Many future avenues of research, both observational and theoretical, remain for the field of DSs. It is interesting to investigate whether or not they can be seen directly, e.g. by JWST or SNAP. It is important to pursue the indirect evidence. Although current neutrino detectors such as ICECUBE do not have the angular resolution to see neutrinos due to DM annihilation from a single DS, given a star formation rate (unfortunately highly uncertain), one can estimate the contribution to the neutrino background. Similarly, one can study the synchrotron emission from DM annihilation around the black hole remnants of DSs to ascertain whether or not it can explain the observed radio excess in ARCADE [48]. On the theoretical side, we plan to study the stellar structure of DSs with capture included; then DSs may end up significantly larger, possibly swallowing all the baryons in the minihalo. The dependence of our results on the concentration parameter will also be interesting to examine.

In conclusion, the first stars to form in the Universe may be DSs powered by DM heating rather than by fusion. Our work indicates that they may be very large ($800 M_\odot$ for $100\,\text{GeV}$ mass WIMPs). Once DS are found, one can use them as a tool to study the properties of WIMPs.

Acknowledgments

References

[1] Spolyar D, Freese K and Gondolo P 2007 arXiv:astro-ph/0705.0521
[2] Ripamonti E and Abel T 2005 arXiv:astro-ph/0507130
[3] Barkana R and Loeb A 2001 *Phys. Rep.* **349** 125
[4] Bromm V and Larson R B 2004 *Annu. Rev. Astron. Astrophys.* **42** 79
[5] Yoshida N, Omukai K and Hernquist L 2008 *Science* **321** 669–71
[6] Abel T, Bryan G L and Norman M L 2002 *Science* **295** 93
[7] Bromm V, Coppi P S and Larson R B 2002 *Astrophys. J.* **564** 23
[8] Yoshida N *et al* 2006 *Astrophys. J.* **652** 6
[9] Komatsu E *et al* (WMAP Collaboration) 2008 arXiv:0803.0547
[10] Jungman G, Kamionkowski M and Griest K 1996 *Phys. Rep.* **267** 195
[11] Lewin J D and Smith P F 1996 *Astropart. Phys.* **6** 87–112
[12] Primack J, Seckel D and Sadoulet B 1988 *Annu. Rev. Part. Nucl. Sci.* **38** 751
[13] Bertone G, Hooper D and Silk J 2005 *Phys. Rep.* **405** 279
[14] Krauss L M, Freese K, Press W and Spergel D 1985 *Astrophys. J.* **299** 1001
[15] Srednicki M, Olive K A and Silk J 1987 *Nucl. Phys.* B **279** 804
[16] Freese K 1986 *Phys. Lett.* B **167** 295
[17] Krauss L M, Srednicki M and Wilczek F 1986 *Phys. Rev.* D **33** 2079
[18] Bouquet A and Salati P 1989 *Astron. Astrophys.* **217** 270B
[19] Salati P and Silk J 1989 *Astrophys. J.* **338** 24
[20] Moskalenko I V and Wai L L 2007 *Astrophys. J.* **659** L29 (arXiv:astro-ph/0702654)
[21] Scott P, Fairbairn M and Edsjo J 2008 arXiv:0810.5560
[22] Scott P, Edsjo J and Fairbairn M 2007 arXiv:0711.0991
[23] Bertone G and Fairbairn M 2008 *Phys. Rev.* D **77** 043515 (arXiv:0709.1485)
[24] Navarro J F, Frenk C S and White S D M 1996 *Astrophys. J.* **462** 563
[25] Blumenthal G R, Faber S M, Flores R and Primack J R 1986 *Astrophys. J.* **301** 27

[26] Natarajan A, Tan J C and O'Shea B W 2008 arXiv:0807.3769
[27] Young P 1980 *Astrophys. J.* **242** 1232
[28] Freese K, Gondolo P, Sellwood J A and Spolyar D 2008 arXiv:0805.3540
[29] Ripamonti E, Mapelli M and Ferrara A 2007 *Mon. Not. R. Astron. Soc.* **375** 1399
[30] Hollenbach D and McKee C F 1979 *Astrophys. J. Suppl.* **41** 555
[31] Yoshida N, Freese K, Gondolo P and Spolyar D 2009 in preparation
[32] Adriani O *et al* (PAMELA Collaboration) 2009 *Nature* **458** 607 (arXiv:0810.4995)
[33] Collaboration F 2009 arXiv:0905.0025
[34] Sommerfeld A 1931 *Ann. Phys., Lpz* **403** 257
     Arkani-Hamed N, Finkbeiner D P, Slatyer T and Weiner N 2008 arXiv:0810.0713
     Cirelli M and Strumia A 2008 arXiv:0808.3867 [astro-ph]
[35] Freese K, Bodenheimer P, Spolyar D and Gondolo P 2008 arXiv:0806.0617
[36] Tan J C and McKee C F 2004 *Astrophys. J.* **603** 383
[37] O'Shea B W and Norman M L 2006 *Astrophys. J.* **648** 31
[38] Heger A and Woosley S E 2002 *Astrophys. J.* **567** 32
[39] Li Y X *et al* 2006 arXiv:astro-ph/0608190
[40] Freese K, Spolyar D and Aguirre A 2008 *J. Cosmol. Astropart. Phys.* JCAP11(2008)014 (arXiv:0802.1724)
[41] Iocco F 2008 *Astrophys. J.* **677** L1 (arXiv:0802.0941)
[42] Iocco F, Bressan A, Ripamonti E, Schneider R, Ferrara A and Marigo P 2008 arXiv:0805.4016
[43] Taoso M, Bertone G, Meynet G and Ekstrom S 2008 arXiv:0806.2681
[44] Yoon S C, Iocco F and Akiyama S 2008 arXiv:0806.2662
[45] Pelupessy F I, Di Matteo T and Ciardi B 2007 arXiv:astro-ph/0703773
[46] Johnson J L and Bromm V 2007 *Mon. Not. R. Astron. Soc.* **374** 1557
[47] Alvarez M A, Wise J H and Abel T 2008 arXiv:0811.0820
[48] Seiffert M *et al* 2009 arXiv:0901.0559
[49] Ohkubo T *et al* 2006 *Astrophys. J.* **645** 1352
[50] Schleicher D R G, Banerjee R and Klessen R S 2008 arXiv:0809.1519
[51] Bambi C, Spolyar D, Dolgov A D, Freese K and Volonteri M 2008 arXiv:0812.0585