STEellar STRUCTURE OF DARK STARS: A FIRST PHASE OF STELLAR EVOLUTION RESULTING FROM DARK MATTER ANNIHILATION

Katherine Freese,1 Peter Bodenheimer,2 Douglas Spolyar,3 and Paolo Gondolo4

Received 2008 June 25; accepted 2008 August 19; published 2008 September 9

ABSTRACT

Dark stars are the very first phase of stellar evolution in the history of the universe: the first stars to form (typically at redshifts $z \sim 10–50$) are powered by heating from dark matter (DM) annihilation instead of fusion (if the DM is made of particles which are their own antiparticles). We find equilibrium polytropic configurations for these stars; we start from the time DM heating becomes important ($M \sim 1–10 M_\odot$) and build up the star via accretion up to $1000 M_\odot$. The dark stars, with an assumed particle mass of 100 GeV, are found to have luminosities of a few times $10^4 L_\odot$, surface temperatures of 4000–10,000 K, radii $\sim 10^{14}$ cm, and lifetimes of at least 0.5 Myr and are predicted to show lines of atomic and molecular hydrogen. Dark stars look quite different from standard metal-free stars without DM heating: they are far more massive (e.g., $\sim 800 M_\odot$ for 100 GeV WIMPs), cooler, and larger and can be distinguished in future observations, possibly even by JWST or TMT.

Subject headings: dark matter

1. INTRODUCTION

The first stars in the universe mark the end of the cosmic dark ages, reionize the universe, and provide the enriched gas required for later stellar generations. They may also be important as precursors to black holes that coalesce and power bright early quasars. The first stars are thought to form inside the dark matter (DM) halos of mass $10^5–10^6 M_\odot$ at redshifts $z \sim 10–50$ (Yoshida et al. 2003). These halos consist of 85% DM and 15% baryons in the form of metal-free gas made of H and He. Theoretical calculations indicate that the baryonic matter cools and collapses via H, He, cooling (Peebles & Dicke 1968; Matsuda et al. 1971; Hollenbach & McKee 1979) into a single small protostar (Omukai & Nishi 1998) at the center of the halo (for reviews, see Ripamonti & Abel 2005; Barkana & Loeb 2001; Bromm & Larson 2004).

Previously, Spolyar et al. (2008, hereafter Paper I) first considered the effect of DM particles on the first stars during their formation. Any DM particle which is capable of annihilating with itself in such a way as to give the correct relic abundance today will also annihilate wherever the DM density is high. The first protostars and stars are particularly good sites for annihilation because they form at high redshifts (density scales as $(1+z)^3$) and in the high-density centers of DM halos. Paper I found that DM annihilation provides a powerful heat source in the first stars, a source so intense that its heating overwhelms all cooling mechanisms. Paper I suggested that the very first stellar objects might be dark stars (DS), a new phase of stellar evolution in which the DM—while only a negligibly small fraction of the star’s mass—provides the key power source for the star through DM heating. Note that the term “dark” refers to the power source, not the luminosity. In this Letter, we continue the work originally suggested in Paper I by studying the DS structure.

The canonical example of particle DM is weakly interacting massive particles (WIMPs), which automatically provide the right amount of DM, i.e., $\sim 24\%$ of the current energy density of the universe. In many theories WIMPs are their own antiparticles and annihilate with themselves in the early universe, leaving behind this relic density. In particular, the neutralino, the supersymmetric partner of the W, Z, and Higgs bosons, is a strong candidate (reviewed by Jungman et al. 1996). As our canonical values, we use the standard $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm$^3$ s$^{-1}$ for the annihilation cross section and $m_\chi = 100$ GeV for the particle mass. A companion paper will generalize to other masses and cross sections. The analysis in this Letter could apply equally well to other DM candidates.

WIMP annihilation produces energy at a rate per unit volume

$$\dot{Q}_{\text{DM}} = \langle \sigma v \rangle \rho_\chi^2 / m_\chi,$$  

where $\rho_\chi$ is the energy density of the WIMPs. In the early stages of Population III (Pop III) star formation, when the gas density is low ($n \lesssim 10^4$ cm$^{-3}$), most of the annihilation products simply escape from the protostar without heating it (Ripamonti et al. 2007). However, a crucial transition takes place (Paper I) when the gas density of the collapsing protostar exceeds a critical value at which point most of the annihilation energy is trapped in the star. For a 100 GeV particle, at hydrogen density $\sim 10^{13}$ cm$^{-3}$, typically 1/3 of the energy is lost to neutrinos that escape the star, while the other 2/3 of the energy is trapped inside the star (Paper I). Hence the luminosity from the DM heating is

$$L_{\text{DM}} \sim $$

where $dV$ is the volume element.

The properties of the collapsing protostellar clouds have been given by 3D simulations (Abel et al. 2002; Gao et al. 2007). At the time when the density reaches $n = 10^{13}$ cm$^{-3}$, the critical value for 100 GeV particles, Paper I found a proto-DS in equilibrium with a radius of 17 AU and a mass of 0.6 $M_\odot$, giving a DM luminosity of $\sim 140 L_\odot$. As more mass accretes onto the DS, the protostellar luminosity begins to exceed the DM heating, so that the protostar is no longer in thermal equilibrium. Thus, it must contract, which increases the DM density until the DM heating as given in equation (2) matches its radiated luminosity.
In this calculation, we assume that such a situation can be reached, and we then build up the dark star from a few solar masses up to 1000 $M_\odot$, finding its structure as a polytrope in hydrostatic and thermal equilibrium at each step in mass. As we build up the star, more DM is pulled into the star via adiabatic contraction and subsequently annihilates; we find that the annihilation fuel contained in the star can thereby last $\sim 10^6$ yr. While the results of this Letter were being written, a Letter appeared by Iocco et al. (2008) that included DM heating in Pop III pre–main-sequence evolution of a set of stars of fixed mass, finding that the quasi-hydrostatic contraction is halted for times of $2 \times 10^3$ (2 $\times 10^4$) yr for stars of mass 600 (9) $M_\odot$, at radii $\approx$ a few AU. During the evolution of a DS, additional WIMPs could be captured via scattering off of nuclei. The cross section for scattering is very uncertain. For $\sigma < 10^{-39}$ cm$^2$ we find that a DM particle undergoes less than one scattering event in 1 Myr in the evolutionary stage considered in this Letter. The experimental bounds for 100 GeV particles from DM searches are $\sigma \lesssim 2 \times 10^{-43}$ cm$^2$ for the spin-independent case (R. Gaitskill et al. 2008) and $\sigma \lesssim 3.5 \times 10^{-39}$ cm$^2$ for the spin-dependent case (Savage et al. 2004). Hence, we assume negligible scattering here. However, at later stages of the evolution, once the DM density becomes too low to support the star via heating, the DS contracts until nuclear burning sets in. At these higher densities, scattering at the experimentally allowed limit would become important. DM passing through the star could be captured and again drive DM heating. These effects have been considered for main-sequence and pre–main-sequence DSs by Freese et al. (2008b), Iocco (2008), and Iocco et al. (2008), who find that the DM heating could dominate nuclear fusion as long as the background DM density (from which the capture takes place) remains high enough. Future work will further consider scattering in the DS.

We also cite previous work on DM annihilation in today’s stars (less powerful than in the first stars): Krauss et al. (1985), Bouquet & Salati (1989), Salati & Silk (1989), Moskalenko & Wai (2007), Scott et al. (2007), and Bertone & Fairbairn (2007).

2. EQUILIBRIUM STRUCTURE

We make the assumption that the dark stars can be described as polytropes in hydrostatic equilibrium

$$P = K \rho^{1 + \frac{f}{\ln n}}$$

where $P$ is the pressure, $\rho$ is the density, and the constant $K$ is determined once the total mass and radius are specified (Chandrasekhar 1939). Pre–main-sequence stellar models are adequately described by polytropes in the range $n = 1.5$ (fully convective) to $n = 3$ (fully radiative). For a given stellar mass, we iterate the radius of the model to find the point of thermal equilibrium, that is, where the total DM heating matches the radiated luminosity. We then add 1 $M_\odot$, calculate a new equilibrium, and continue up to 1000 $M_\odot$. In the standard scenario of formation of the first stars, it was found that at $n \sim 10^3$ cm$^{-3}$, the mass of the protostellar cloud exceeds the Jeans mass (e.g., Bromm et al. 2002). This amount of baryonic material, $\sim$1000 $M_\odot$, could fall down onto the DS and in the process bring in more DM with it.

2.1. DM Densities

The DM densities in the protostar are derived as described in Paper I. We take a 10$^3$ $M_\odot$ halo composed of 85% DM and 15% baryons. We take an initial Navarro et al. profile (1996) with a concentration parameter $c = 2$ at $z = 20$ in a standard ΛCDM universe. We follow the DM response to the changing baryonic gravitational potential as the protostellar gas condenses. As the baryons come to dominate the potential well in the core, they pull the DM particles inward. We use the simple adiabatic contraction method of Blumenthal et al. (1986), Barnes & White (1984), and Ryden & Gunn (1987) (hereafter the Blumenthal method) to estimate the resultant DM density profile. The method has the limitation that all halo particles are taken to be on circular orbits. Recently (Freese et al. 2008a), we did an exact calculation using an algorithm originally developed by Young (1980) which takes into account radial motions as well. The results for the DM density agree with those from the Blumenthal method to within a factor of 2. This factor of 2 may be compensated by the fact that recent simulations via Via Lactea II (Diemand et al. 2008) find initial DM density profiles that are steeper in the inner core ($\rho \propto r^{-3}$) rather than $\rho \propto 1/r$. Hence, the Blumenthal method should give reasonable results. The DM density profile in the DS is calculated at each iteration of the stellar structure, so that the DM luminosity can be determined.

2.2. Basic Equations

The basic equation is that of hydrostatic equilibrium

$$\frac{dP}{dr} = -\rho \frac{GM_*}{r^2}$$

where $dM/dr = 4\pi r^2 \rho(r)$, $\rho(r)$ is the total density (gas plus DM) at radius $r$, and $M_*$ is the enclosed mass within radius $r$. The temperature of the gas $[T(r)]$ is determined from the equation of state of a mixture of ideal gas and radiation:

$$P(r) = \frac{\rho k T(r)}{m_p m} + \frac{1}{3} \frac{\alpha T(r)^4}{P_r} = P_* + P_{rad},$$

where $k_B$ is Boltzmann’s constant, $m_p$ is the atomic mass unit, and the mean atomic weight $\bar{m} = (2X + 3/4Y)^{-1} = 0.588$. We take the H mass fraction $X = 0.76$ and the He mass fraction $Y = 0.24$. In the resulting models $T \gg 10,000$ K except near the very surface, so the H and He are ionized and the H$_2$ is dissociated. We will find the radiation pressure to be important once the DS becomes heavier than $\sim$100 $M_\odot$. We also require the DS to be in thermal equilibrium,

$$L_* = 4\pi \sigma_B R_*^2 T_{eff}^4 = L_{DM}.$$
The initial protostellar core of 3\,M∗. The set of upper (lower) solid curves correspond to the baryonic (DM) density profile (values given on left axis) at different masses and times. Dashed lines: Luminosity L_{\text{DM}} integrated out to radius $r$ for the masses 12 and 1000 $M_\odot$, in solar units (values given on the right axis).

3. RESULTS

Table 1 and Figure 1 illustrate our results for standard parameters for $M_\ast = 10$–1000 $M_\odot$ and for $n = 1.5$. In the table we present the sequence of central temperature $T_c$, photospheric radius $R_\ast$, central gas density $\rho_\ast$, central DM density $\rho_{\ast,*}$, stellar luminosity (equal to DM heating luminosity) $L_\ast$, surface temperature $T_{\text{surf}}$, total DM mass inside the star $M_{\text{DM}}$, and time evolved since DM heating dominates inside the star. At 1000 $M_\odot$, $\rho_\ast$ is far lower than for any metal-free zero-age main-sequence star. Figure 1 plots the baryon and DM density profiles. The DM density is many orders of magnitude lower than the baryon density throughout the evolution, and yet the DM annihilation powers the star. As time goes on, one can see that the DM is depleted in the interior regions of the star, due to annihilation, and the density becomes very nearly constant. The plot of $L_{\text{DM}}(r)$, the dark matter luminosity integrated out to radius $r$, shows that the heating is spread out over much of the volume of the DS; thus, it is not particularly sensitive to changes in the details of the adiabatic contraction model. By the time the DS reaches 1000 $M_\odot$, the amount of DM in the star is only $1/3 M_\odot$, and $1/3$ of the DM in the DS has annihilated away. It is not known whether or not the DM inside the DS can be repopulated from DM particles in the $10^6 M_\odot$ halo surrounding it; this question would require numerical resolution not currently available.

In the future, it would be interesting to study the accretion process in more detail. It is likely to proceed via the formation of a disk with an accompanying accretion luminosity. In the standard Pop III star formation process of accretion onto a small $10^{-3} M_\odot$ nugget, the luminosity has an accretion-driven phase; here, on the other hand, the accretion luminosity of the much larger DS is always negligible. In any case our treatment of the structure of the stellar interior is probably unchanged by the presence of the disk. Previously McKee & Tan (2007) have studied the role of angular momentum in Pop III stars in the absence of DM. One should reconsider angular momentum in the case of DS as well.

![Fig. 1](image_url)

**Fig. 1.** Evolution of a dark star ($n = 1.5$) as mass is accreted onto the initial protostellar core of 3 $M_\odot$. The set of upper (lower) solid curves correspond to the baryonic (DM) density profile (values given on left axis) at different masses and times. Dashed lines: Luminosity $L_{\text{DM}}$ integrated out to radius $r$ for the masses 12 and 1000 $M_\odot$, in solar units (values given on the right axis).
qualitatively the same. For $M_* = 600$ $M_\odot$, the $n = 3$ case gives $T_{\text{eff}} = 9100$ K, $R_* = 6.0 \times 10^{13}$ cm, $L_* = 4.6 \times 10^6 L_\odot$, and $T = 2.2 \times 10^6$ K; while the $n = 1.5$ case gives $T_{\text{eff}} = 6370$ K, $R_* = 1.0 \times 10^{11}$ cm, $L_* = 3.04 \times 10^8 L_\odot$, and $T = 6.88 \times 10^5$ K. Thus, the results for the $n = 1.5$ polytrope give the basic picture. Note that DS have much lower $T_{\text{eff}}$ than their standard metal-free (Pop III) main-sequence counterparts in the absence of DM, which radiate at $T_{\text{eff}} > 30,000$ K. This difference gives a markedly different observable signature for the DS than for the standard Pop III stars.

4. CONCLUSIONS

We have followed the growth of equilibrium dark stars, powered by DM annihilation, up to 1000 $M_\odot$. The objects have sizes of a few AU and central $T \approx 10^5$–10$^6$ K. Sufficient DM is brought into the star by contraction from the DM halo to result in a DS which lives at least 0.5 Myr (the lifetime could be significantly longer if DM capture becomes important at the later stages, as long as the background DM density is high enough for capture to take place). Because of the relatively low $T_{\text{eff}}$ (4000–10,000 K), feedback mechanisms for shutting off accretion of baryons, such as the formation of H II regions or the dissociation of infalling H$_2$ by Lyman-Werner photons, are not effective. The implication is that main-sequence stars of Pop III are very massive. This conclusion depends on uncertain parameters such as the DM particle mass, the accretion rate, and scattering, effects that will be studied in future work.

Although DS shine with a luminosity of a few times $10^6 L_\odot$ they would be very difficult to observe at $z \sim 10$–50. One can speculate that pristine regions containing only H and He might still exist to lower redshifts; then DS forming in these regions might be easier to detect. One may hope that the ones that form most recently are detectable by JWST or TMT and differentiable from the standard metal-free Pop III objects. DS are also predicted to have atomic hydrogen lines originating in the warmer photospheres and H$_2$ lines arising from the infalling material, which is still relatively cool. Alternatively, DM may be replenished in the DS by capture and the DS can exist as long as the ambient DM density is high enough; then the DS could persist to low redshift (even to today) with the same observational signatures discussed in this Letter.

It has been argued that Pop III.1 stars (the very first metal-free stars) may constitute at most $\sim$10% of metal-poor stars on observational grounds. Heger & Woosley (2002, hereafter HW) showed that for $140 M_\odot < M < 260 M_\odot$, pair instability (SN) leads to odd-even effects in the nuclei produced that are strongly constrained by observations. Thus, if Pop III.1 stars are really in this mass range, one would have to constrain their abundance. For $M > 260 M_\odot$, HW find that no SN occurs, and the end result of stellar evolution is collapse of the entire star into a black hole. We expect, based on extension of the $n = 3$ calculation, that our DS runs out of DM at about 700–900 $M_\odot$ (for $m_\chi = 100$ GeV). Then it must contract to the main sequence, where nuclear burning sets in, and further evolution would proceed as in HW. Alternatively, the evolution could proceed as described by Ohkubo et al. (2006), who found that metal-free stars of 500 and 1000 $M_\odot$, taking into account two-dimensional effects, did blow up as SN, leaving about half their mass behind in a black hole. In this case the SN might be observable signatures of DS, distinguishable since they arise from such high-mass stars. The end product in either case would be a plausible precursor of the otherwise unexplained $10^6 M_\odot$ black holes at $z = 6$ (N. Yoshida et al. 2008, in preparation).

We acknowledge support from the DOE and MCTP via the University of Michigan (K. F.); NSF grant AST-0507117 and GAANN (D. S.); NSF grant PHY-0456825 (P. G.). K. F. acknowledges the hospitality of the Physics Department at the University of Utah. K. F. and D. S. are extremely grateful to Chris McKee and Pierre Salati for their encouragement of this line of research and to A. Aguirre, L. Bildsten, R. Bouwens, J. Gardner, N. Murray, J. Primack, M. Rieke, C. Savage, J. Sellwood, J. Tan, and N. Yoshida for helpful discussions.

REFERENCES

Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Barkana, R., & Loeb, A. 2001, Phys. Rep., 349, 125
Barnes, J., & White, S. D. M. 1984, MNRAS, 211, 753
Bertone, G., & Fairbairn, M. 2007, preprint (arXiv:0711.1485)
Blumenthal, G. R., Faber, S. M., Flores, R., & Primack, J. R. 1986, ApJ, 301, 27
Bouquet, A., & Salati, P. 1989, ApJ, 346, 284
Bromm, V., Coppi, P. S., & Larson, R. B. 2002, ApJ, 564, 23
Bromm, V., & Larson, R. B. 2004, ARA&A, 42, 79
Chandrasekhar, S. 1939, An Introduction to the Theory of Stellar Structure (Chicago: Univ. Chicago Press)
Diemand, J., Kuhlen, M., Madau, P., Zemp, M., Moore, B., Potter, D., & Stadel, J. 2008, preprint (arXiv:0805.1244)
Freed, K., Gondolo, P., Sellwood, J. A., & Spolyar, D. 2008a, preprint (arXiv:0805.3540)
Freed, K., Spolyar, D., & Aguirre, A. 2008b, preprint (arXiv:0802.1724)
Gao, L., Abel, T., Frenk, C. S., Jenkins, A., Springel, V., & Yoshida, N. 2007, MNRAS, 378, 449
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532 (HW)
Hollenbach, D., & McKee, C. F. 1979, ApJS, 41, 555
Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943
Iocco, F. 2008, ApJ, 677, L1
Iocco, F., Bressan, A., Ripamonti, E., Schneider, R., Ferrara, A., & Marigo, P. 2008, preprint (arXiv:0805.4016)
Jungman, G., Kamionkowski, M., & Griest, K. 1996, Phys. Rep., 267, 195
Krauss, L., Freese, K., Press, W., & Spergel, D. N. 1985, ApJ, 299, 1001
Lenzoni, P., Chernoff, D. F., & Salpeter, E. 1991, ApJS, 76, 759
Matsuda, T., Sato, H., & Takeda, H. 1971, Prog. Theor. Phys., 46, 416
McKee, C. F., & Tan, J. C. 2007, preprint (arXiv:0711.1377)
Moskalenko, I. V., & Wai, L. L. 2007, ApJ, 659, L29
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Ohkubo, T., et al. 2006, ApJ, 645, 1352
Omukai, K., & Nishi, R. 1998, ApJ, 508, 141
Peebles, P. J. E., & Dicke, R. H. 1968, ApJ, 154, 891
Ripamonti, E., & Abel, T. 2005, preprint (astro-ph/0507130)
Ripamonti, E., Mapelli, M., & Ferrara, A. 2007, MNRAS, 375, 1399
Ryden, B. S., & Gunn, J. E. 1987, ApJ, 318, 15
Salati, P., & Silk, J. 1989, ApJ, 338, 24
Savage, C., Gondolo, P., & Freese, K. 2004, Phys. Rev. D, 70, 123513
Scott, P., Edsjo, J., & Fairbairn, M. 2007, preprint (arXiv:0711.0991)
Spolyar, D., Freese, K., & Gondolo, P. 2008, Phys. Rev. Lett., 100, 051101
(Triangular Paper I)
Yoshida, N., Abel, T., Hernquist, L., & Sugiyama, N. 2003, ApJ, 592, 645
Young, P. 2008, ApJ, 242, 1232